

PB86-111218

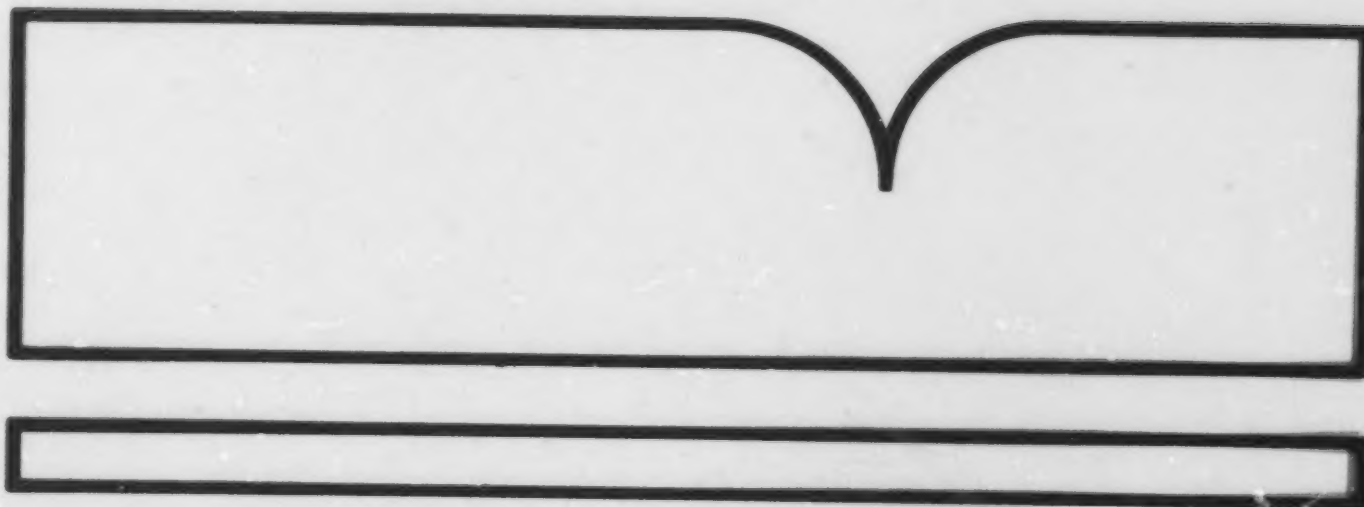
Emissions Assessment for
Refuse-Derived Fuel Combustion

Battelle Columbus Labs., OH

Prepared for

Environmental Protection Agency
Cincinnati, OH

Sep 85



U.S. Department of Commerce
National Technical Information Service

NTIS

EPA/600/2-85/116
September 1985

EMISSIONS ASSESSMENT FOR REFUSE-DERIVED FUEL COMBUSTION

by

Bruce W. Rising
John M. Allen
Battelle Columbus Laboratories
Columbus, Ohio 43201

Contract No. 68-03-2772

Project Officer

Michael Black

Alternate Technologies Division
Hazardous Waste Engineering Research Laboratory
Cincinnati, Ohio 45268

HAZARDOUS WASTE ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA (Please read instructions on the reverse before completing)		
1. REPORT NO. EPA/600/2-85/116	2.	3. RECIPIENT'S ACCESSION NO. PB8 6 111218/AS
4. TITLE AND SUBTITLE EMISSIONS ASSESSMENT FOR REFUSE-DERIVED FUEL COMBUSTION	5. REPORT DATE September 1985	
	6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) Bruce Rising and John Allen	8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Battelle Columbus Laboratories 505 King Ave. Columbus, OH 43201	10. PROGRAM ELEMENT NO.	
	11. CONTRACT/GRANT NO. 68-03-2772	
12. SPONSORING AGENCY NAME AND ADDRESS Hazardous Waste Engineering Research Laboratory Office of Research and Development U.S. EPA Cincinnati, OH 45268	13. TYPE OF REPORT AND PERIOD COVERED Project Report 2/79-10/80	
	14. SPONSORING AGENCY CODE EPA/600/12	
15. SUPPLEMENTARY NOTES Michael Black, P.O.; 513-684-7844		
16. ABSTRACT The RDF and coal were burned in a small spreader-stoker fired boiler. The parameters that were varied in this program were RDF type and amount of coal burned with the RDF. In two experiments a waste chemical, triethanolamine, was added to the fuel, and its destruction efficiency was assessed. Analysis of the flue gases identified low levels of hydrocarbons, nitric oxide, carbon monoxide, and sulfur dioxide. The particulate loadings increased as the percentage of RDF in the total fuel increased. More than half of the particulate loading was submicron in size when RDF was fired without coal. Large quantities of POM's were detected in those experiments in which the shredded and pelletized RDF were fired in the furnace. No dioxins were detected in those tests in which it was analysed. In the experiments in which RDF was the only fuel, lead emissions were several orders of magnitude above the levels detected in the coal base run. Based upon the flue gas analysis, the destruction of the triethanolamine was complete.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES 76
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE \$11.95

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments and the needs of both large and small business in handling their wastes responsibly and economically.

The RDF and coal were burned in a small spreader-stoker fired boiler. The parameters that were varied in this program were RDF type and amount of coal burned with the RDF. In two experiments a waste chemical, triethanolamine, was added to the fuel, and its destruction efficiency was assessed. Analysis of the flue gases identified low levels of hydrocarbons, nitric oxide, carbon monoxide, and sulfur dioxide. The particulate loadings increased as the percentage of RDF in the total fuel increased.

The information contained herein will be of interest to those designers or users who are contemplating or working with a system similar to this co-firing system. Requests for further information regarding the production and utilization of refuse-derived fuel should be directed to the Thermal Destruction Branch, HWERL, Cincinnati.

David G. Stephan, Director
Hazardous Waste Engineering Research Laboratory

ABSTRACT

This program has examined in depth the emissions resulting from the combustion of refuse derived fuels (RDF) and coal. The two RDF's used were Eco-Fuel II, a pulverized product, and a shredded RDF from Americology. Both were pelletized before burning.

The RDF and coal were burned in a small spreader-stoker fired boiler. The parameters that were varied in this program were RDF type and amount of coal burned with the RDF. In two experiments a waste chemical, triethanolamine, was added to the fuel, and its destruction efficiency was assessed.

Analysis of the flue gases identified low levels of hydrocarbons, nitric oxide, carbon monoxide, and sulfur dioxide. The particulate loadings increased as the percentage of RDF in the total fuel increased. More than half of the particulate loading was submicron in size when RDF was fired without coal. Large quantities of POM's were detected in those experiments in which the shredded and pelletized RDF were fired in the furnace. No dioxins were detected in those test in which it was analysed. In the experiments in which RDF was the only fuel, lead emissions were several orders of magnitude above the levels detected in the coal base run. Based upon the flue gas analysis, the destruction of the triethanolamine was complete.

This report was submitted in fulfillment of Contract No. 68-03-2772 by Battelle Columbus Laboratories under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period February, 1979 through October, 1980.

CONTENTS

Foreword	iii
Abstract	iv
Tables	vi
1. Introduction	1
2. Conclusions	3
3. Objective and Scope.	8
4. Related Programs	9
5. Stoker Fired Boiler.	10
6. Fuel Handling and Fuel Characteristics	14
7. Experimental Burning Program	23
8. Experimental Results	28
9. Data Reproducibility	67
10. Application of These Test Results.	68
References	69

TABLES

<u>Number</u>		<u>Page</u>
1	Summary of Emission Measurements Burning Coal and Densified RDF in Stoker Fired Boiler.	4
2	Chemical Analysis of Fuels	15
3	Trace Metals Analysis of Fuels	16
4	Toxic Metals Analysis of Fuels	18
5	Integrated Fuel Chemical Composition	22
6	Experimental Sampling Matrix	24
7	Experimental Conditions.	29
8	Sulfur Emission Data	31
9	Nitrogen Emission Data	32
10	Chloride Emission Data	34
11	Particulate Emission Data.	37
12	Particulate Size Distribution.	38
13	Fire Tube Fly Ash Chemical Analysis - Test 1, Coal . . .	39
14	Firetube Fly Ash Chemical Analysis - Test 2, Coal + Eco-Fuel II	40
15	Firetube Fly Ash Chemical Analysis - Test 3, Eco-Fuel II	41
16	Bottom Ash Chemical Analysis - Test 2, Coal + Eco-Fuel II.	43
17	Bottom Ash Chemical Analysis - Test 2, Coal + Eco-Fuel II.	44
18	Chemical Analysis of Bottom Ash from Other Stoker Fired Boiler.	45
19	Hydrocarbon Analysis of Flue Gas by Gas Chromatography - Test 1, Coal	47
20	Hydrocarbon Analysis of Flue Gas by Gas Chromatography - Test 2, Eco-Fuel II + Coal	48
21	Hydrocarbon Analysis of Flue Gas by Gas Chromatography - Test 3, Eco-Fuel II.	49
22	Hydrocarbon Analysis of Flue Gas by Gas Chromatography - Test 4, Americology + Coal	50
23	Hydrocarbon Analysis of Flue Gas by Gas Chromatography - Test 5, Americology.	51
24	Hydrocarbon Analysis of Flue Gas by Gas Chromatography - Test 6, Eco-Fuel II + Coal + Hazardous Waste.	52
25	SASS Samples Analyzed.	54
26	Toxic Metals Analyses.	55
27	Trace Metals Analysis of Respirable Particulates	56
28	Organic Materials Extracted from Flue Gas and Respirable Particulates	60
29	Organic Characterization of Total Sample	61
30	Organic Characterization of Liquid Chromatography Fractions	62
31	POM Emissions.	64
32	Dioxin Analyses.	65

SECTION 1

INTRODUCTION

The use of waste materials as a fuel substitute is a concept that has received close examination in recent years. Waste-to-energy combustion systems have been used for many years in Europe. However, the U.S. approach is somewhat different from the approach used in Europe. In the U.S. a major effort has been organized to promote the combustion of a refuse derived fuel (RDF) in waste-to-energy system in contrast to the mass burning approach utilized in Europe. An RDF is a processed municipal solid waste which has had as much non-combustible material (sand, metals, etc.) removed as is technically and economically feasible. The combustible part of the waste (paper, plastics, etc) is then subjected to shredding to reduce the size of the fuel. The final product (RDF) may then be burned in a suspension burning mode, a turbulent well mixed bed, or a fixed bed.

The RDF may also be further processed into a form known as densified RDF (d-RDF) which requires pelletizing, briquetting or otherwise compacting the RDF into larger more dense pieces.

In the Battelle study, a pelletized form of RDF was used as a fuel in the emissions assessment program. Two types of RDF (Eco-Fuel II and Americology) were fired with and without the addition of coal in a small spreader-stoker fired boiler. A complete assessment of the flue gases was performed by continuous monitors and by batch collection techniques and analysis techniques. Also, Level One⁽¹⁾ analyses were performed on the gaseous and particulate samples extracted by the SASS train.

A further addition to the experimental program required an assessment of the destruction of a hazardous waste material that was co-fired with the coal/RDF fuel. The degree of destruction of the

waste was determined by monitoring the anticipated by-products of the waste material. This waste material was mixed with the RDF before pelletization, and the resulting pellets were co-fired with coal.

SECTION 2

CONCLUSIONS

This section summarizes the emissions measured and analyzed for the seven tests conducted. The distinctions between test runs were primarily related to the different compositions of the fuels fired, although the physical properties of the RDF fuels presumably also affected the emissions and cannot be overlooked. Other than fuels, there were no major changes in feed system or boiler operation during the test program. When coal and RDF were co-fired, each fuel provided half of the total heat input to the furnace.

The seven tests conducted were:

- Coal fired only
- Coal co-fired with Eco-Fuel II (50/50 by heat content)
- Eco-Fuel II fired only
- Coal co-fired with Americology (50/50 by heat content)
- Americology fired only
- Coal co-fired with Eco-Fuel II + 10 wt percent hazardous waste
- Coal co-fired with Eco-Fuel II + 5 wt percent hazardous waste.

The weight fraction of hazardous waste that is reported is the weight of hazardous waste contained in the Eco-Fuel II pellets, not the weight fraction of waste in the coal + Eco-Fuel II.

Table 1 summarizes the emissions that were observed. The average CO measured in the stack is shown for each test. The excess air in each test was maintained at a level just sufficient to eliminate CO in the stack gas, and the average CO during all tests was less than 20 ppm.

TABLE 1. SUMMARY OF EMISSION MEASUREMENTS BURNING
COAL AND DENSIFIED RDF IN STOKER FIRED BOILER

Test No.	1	2	3	4	5	6	7
Fuel Fired(1)	Coal Only	Coal + Eco-Fuel II	Eco-Fuel II Only	Coal + Americology	Americology Only	Coal + Eco-Fuel II + TEA(2)	Coal + Eco-Fuel II + TEA(2)
STACK EMISSIONS							
CO ₂ , percent	8.5	9.4	8.5	4.9	8.5	8.7	9.7
Particulates mg/M ³	145	167	111	323	417	186	206
SO ₂ ppm	477	462	403	271	98	394	388
NO _x ppm	200	175	170	150	220	260	251
Cl-(3) ppm	37	67	12	115	245	ND	ND
Organics(3) mg/M ³	?	576	965	1170	2870	ND	ND
POM(3), mg/M ³	ND	ND	12.1	19.9	55.0	ND	ND

ND - not determined.

(1) Coal + RDF runs used fuels on a 50-50 basis based on heating value

(2) Triethanol amine, simulating a hazardous waste, was incorporated into RDF fuel pellets @ 10 and 5 wt percent in runs 6 and 7 respectively.

(3) Emitted in gaseous form.

PARTICULATE EMISSIONS

The boiler used in these tests did not have a specific particulate control device such as a cyclone, although small amounts of fly ash settled in the boiler tubes. With Eco-Fuel II pellets burning as the only fuel, the stack emissions were lower than when burning only coal, or when burning both coal and pelletized Eco-Fuel II. Burning the Americology pellets resulted in appreciably higher particulate emissions than when burning Eco-Fuel pellets.

The particles less than 1 μm in diameter comprised the largest fraction of the particulate concentration in experiments in which RDF was used. In the coal-only run (Test 1), the submicron particulates comprised 20 percent of the total loading. In the 3 tests in which coal and Eco-Fuel II were co-fired (Tests 2, 6, and 7), the submicron particles comprised approximately 55 percent of the total particulate loading. In the experiment which used Eco-Fuel as the only fuel (Test 2), the submicron particulates comprised 83 percent of the total loading, although this experiment had the lowest total particulate concentration. The experiments in which the Americology RDF was co-fired with coal (Test 4) and then fired as the only fuel (Test 5), the submicron particulate loadings comprised 71 percent and 85 percent of the total loading, respectively. Also, these two experiments produced the highest total particulate concentrations.

Based on the data collected, it is evident that both RDF's have a tendency to produce large quantities of submicron particulate matter; more than when burning coal. Also, a pale blue haze was evident at the stack during the two Americology tests, indicating the presence of a large amount of small-sized particulates. The fact that this haze was not observed during the Eco Fuel tests may be attributed to the lower concentrations of submicron particulates in the gases, the higher strength of the Eco-Fuel pellets, or the chemical/physical processing that produced the Eco-Fuel.

SO₂

The SO₂ emissions ranged from a high value of approximately 480 ppm in the coal-only experiment (Test 1) to a low value of approximately 98 ppm in the Americology only experiment (Test 5). Although the Eco-Fuel II had

a lower sulfur content than coal on a weight basis, the sulfur content per Btu was nearly the same. Thus, in comparison of tests with and without coal co-firing, only a small reduction in S emissions were achieved in the Eco-Fuel runs. The fraction of sulfur fired that was emitted as SO_2 varied between 75 and 100 percent of the sulfur fired in all runs.

NO_x

The NO emissions varied from a low of 150 ppm in tests firing coal + Americology (Test 4) to a high of 260 ppm in tests firing coal + Eco-Fuel II (Test 6) in which triethanolamine had been added to the Eco-Fuel II. Since the addition of triethanolamine raised the nitrogen content of the fuel, it would be expected that the NO emissions would increase. In those tests in which no triethanolamine had been added, the NO levels ranged from 150 ppm to 220 ppm. Thus, the addition of the amine had a perceptible but small influence on NO_x emissions.

When the RDF was co-fired with coal, the nitrogen emitted as NO represented approximately one quarter of the fuel-bound nitrogen. Higher emissions of NO relative to the nitrogen in the fuel were observed in the RDF-only test runs.

CHLORIDES

As expected, chloride emissions increased as the chloride concentration in the fuel increased. The lowest stack concentrations, 12.6 ppm were recorded in the coal-only test. The highest concentrations, 245 ppm were recorded in the Americology test.

A chloride mass balance was achieved in only 2 tests, one in which the Americology + coal was the fuel (Test 4), the other in which the Americology was the only fuel (Test 5). In the test in which Eco-Fuel II was the only fuel, 10 percent of the total chloride was accounted for in the flue gases and flyash. In the coal and the coal + Eco-Fuel II tests (Tests 1 and 2) 36.7 and 67.0 percent, respectively, of the chlorides entering the boiler with the fuel were accounted for in the flue gas.

TOTAL HYDROCARBONS (THC)

The hydrocarbon emissions, as measured by the on-line monitoring instrument, were quite low (<20 ppm) for all tests. The hydrocarbon analyzer (FID) sampled gases that had been filtered through a trap and were heated to 200 °F. It is possible that some hydrocarbon species were scrubbed out of the sampled stack gases before the gases were analyzed, however gas chromatography analyses supported the low hydrocarbon emissions indicated by the FID instrumentation.

ORGANIC SPECIES

Gaseous organic materials extracted from the flue gas by Level 1 procedures were noticeably higher when the Americology was burned than when the Eco-Fuel II was burned. The burning of both RDF's resulted in higher organic emissions than when coal was the only fuel. Measurable organic material was observed in the respirable particle emissions only when burning Americology as the only fuel, and the concentration per cubic meter of the flue gas was about a factor of 50 below the concentration of organics collected from the gas stream itself.

POM

Polycyclic organic materials (POM) were detected and measured in three tests, both in the flue gas and in the suspended particulates. The Americology RDF fired without coal appeared to result in higher POM emissions than the Eco-Fuel II RDF fired without coal. Also, the Americology RDF fired without coal produced more POM's than when co-fired with coal.

DIOXINS

The emissions from the burning of RDF without coal were analyzed for 2,4,7,8 TCDD. No positive identification of this specie was made in either the suspended particulate or the gaseous emissions.

SECTION 3

OBJECTIVE AND SCOPE

The objective of this program was to perform an emissions assessment of the combustion of refuse derived fuels (RDF), both with and without the co-firing of coal. The combustion was in a stoker-fired boiler, with most of the combustion occurring in a fixed bed of burning fuel on a grate. The assessment was performed by sampling gaseous and particulate emissions and by conducting Level One and other analyses on the samples extracted from the flue gas stream. Additionally, chemical analyses were performed on the fuels used, and other effluent solids from the boiler.

The research program included two different RDF's and a low sulfur coal. Each fuel was fired separately and each RDF was co-fired with the coal. The coal was fired separately in one test as a benchmark, permitting comparison of the emissions from the two RDF's with those from coal.

Also, the program included an assessment of the destruction of a hazardous waste material that was co-fired with a coal/RDF fuel. The degree of destruction of the waste was determined by monitoring all of the anticipated by-products of the material. Triethanolamine was used as the hazardous waste material.

SECTION 4

RELATED PROGRAMS

This study is one of three similar simultaneous studies conducted by different contractors with related objectives. The same refuse materials and the same coal were used in each study, but different burning modes were employed. Small laboratory combustion systems were used in all three studies. In a study performed by the Energy Resources Company the coal and RDF were burned in a fluidized bed, whereas in the study conducted by KVB, Inc., a fire-tube boiler was used wherein most of the burning occurred in suspension. The RDF was pelletized before burning in the Battelle study in order to minimize the burning in suspension, thus separating as much as possible the effects of suspension and grate burning. The pelletization of the RDF was done specifically for this purpose, and it is not intended to imply that complete pelletization is the only or the recommended procedure for burning RDF in a spreader-stoker fired boiler. The injection of shredded RDF into a boiler with an active bed of fuel can result in extensive suspension burning, simultaneous with the burning of the heavier pieces in the burning bed with or without coal being fired and burned at the same time.

Each program involved the disposal of a different hazardous material, appropriate to the type of burning being utilized.

SECTION 5

STOKER-FIRED BOILER

A 20 HP spreader stoker-fired boiler was used as the combustion system in this project (see Figures 1). The unit can be fired at approximately 800,000 Btu/hr and contains both overfire and underfire air inlets. The underfire or primary air is supplied from the house air supply system, controlled by a manually operated valve, and monitored by an "ASME" orifice and a manometer. The secondary air is also supplied by the house system, manually controlled, and uses another orifice and manometer. The secondary air is introduced through four horizontal jets, located well above the fixed grate just below the firing door. In this program the side walls of the combustion chamber were lined with fibrous ceramic insulation, in order to operate the bed at a temperature representative of larger commercial boilers. The boiler is a two-pass horizontal firetube boiler, with the hot gases leaving the end of the firebox away from the spreader-stoker. The unit was monitored with 8 thermocouples, a flue gas sampling line, and pressure transducers to monitor air feed rates (see Figure 2).

All fuels were fired with the stoker system shown in Figures 1 and 2. When coal was co-fired with the RDF pellets, the fuels were pre-mixed in a 55 gallon drum, and fed from a hopper to the spreader rotor by the vibrating feeder. No significant segregation of the pellets from the double screened coal was observed in the feed system or in the firebox of the boiler. The different fuels were thus effectively mixed in the burning fuel bed. As burning progressed during each test run, the active bed depth increased, as no ashes were removed during a test run. The tests were all terminated before there was evidence of bed channeling by the over-fire air jets.

MODEL SPREADER STOKER

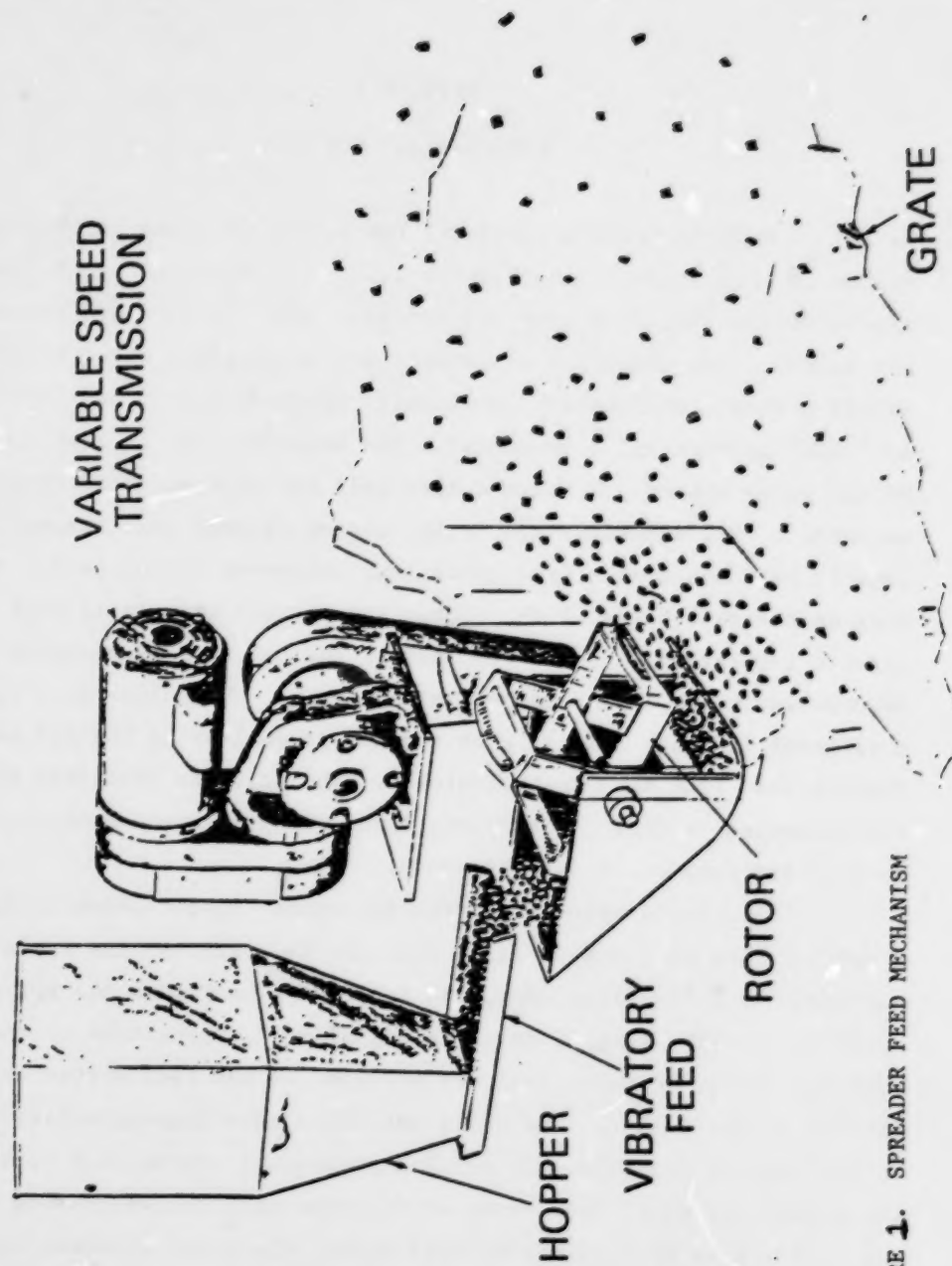


FIGURE 1. SPREADER FEED MECHANISM

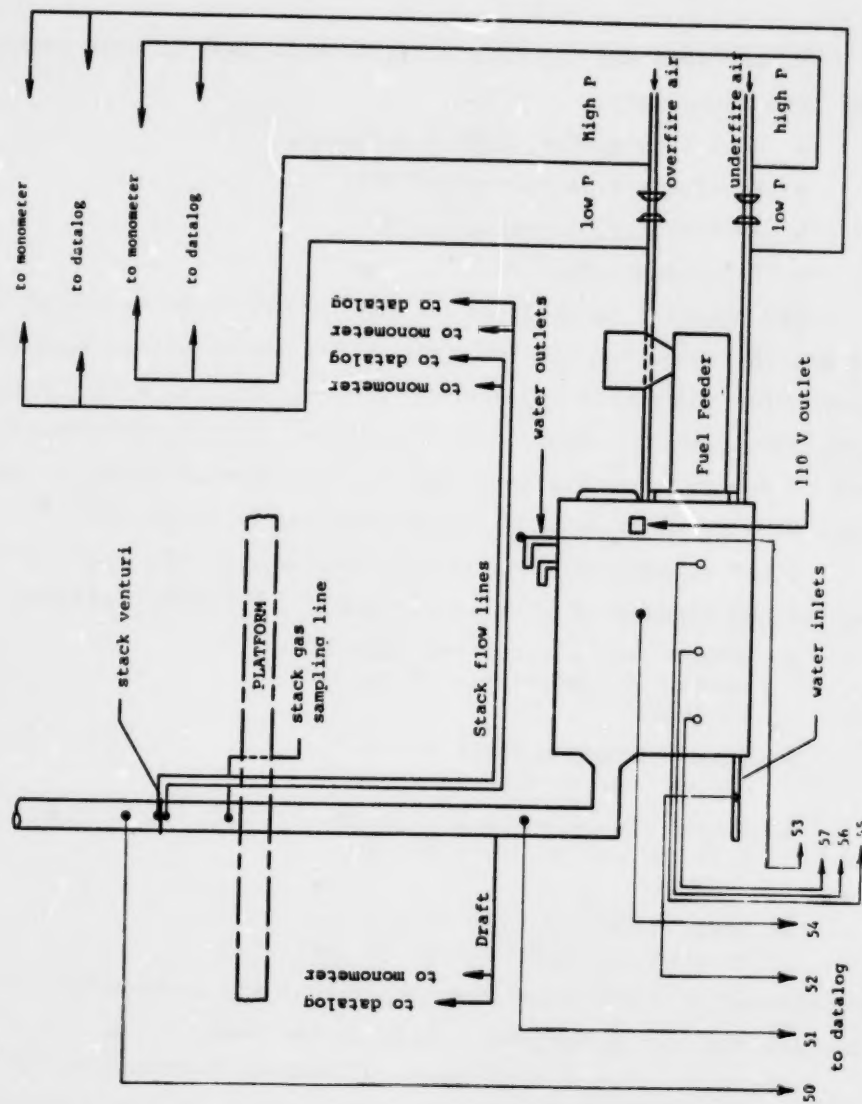


FIGURE 2. STOKER FACILITY MONITORING/SAMPLING POINTS

SECTION 6

FUEL HANDLING AND FUEL CHARACTERISTICS

Three fuels and one fuel additive were used in this experimental program. The fuels were:

- Coal (low-sulfur, double screened)
- Eco-Fuel II, a pulverized RDF
- Americology, a shredded RDF
- Triethanolamine.

The chemical composition of each of the fuels is listed in Table 2. The heating values of the two RDFs (7700 Btu/lb or Eco-Fuel II and 7840 Btu/lb for the Americology) are lower than coal as would be expected since the RDFs contain significant quantities of cellulosic material in the form of paper, wood, and yard wastes. The heating value of cellulosic materials such as wood, is in the 6000-8000 Btu/lb range. (2,3)

Other significant differences between the RDFs and the coal were as follows considered on a weight basis. The RDFs contained

- Higher volatile content (approximately 70 percent vs. 35 percent in coal)
- Higher oxygen content (23-34 percent vs. 8 percent in coal)
- Higher chlorine content (0.23-0.50 percent vs. 0.08 percent in coal)
- Lower sulfur content (0.3-0.70 percent vs. 1.30 percent in coal).

When considered on a Btu basis the comparisons change somewhat, for example the Eco-Fuel had nearly the same sulfur as the coal.

There was also a significant difference between the fuels in the quantity of trace metals. Tables 3 and 4 list the trace metals spark source mass spectroscopic analysis (SSMS) and atomic absorption

TABLE 2. CHEMICAL ANALYSIS OF FUELS

<u>Coal</u>			
<u>Proximate</u>		<u>Ultimate</u>	
	<u>As Rec'd.</u>		<u>As Rec'd.</u>
Percent moisture	5.08	Percent moisture	5.08
Percent Ash	8.78	Percent carbon	70.34
Percent volatile	35.38	Percent hydrogen	4.62
Percent fixed carbon	50.76	Percent nitrogen	1.28
HV:	12484 Btu/lb	Percent chlorine	0.08
	(29,037 KJ/kg)	Percent sulfur	1.30
		Percent ash	8.78
		Percent oxygen	8.52
		(by diff.)	

<u>Eco-Fuel II RDF</u>			
<u>Proximate</u>		<u>Ultimate</u>	
Percent moisture	5.6	Percent moisture	5.6
Percent ash	10.6	Percent ash	10.0
Percent volatile	70.2	Percent carbon	43.8
Percent fixed carbon	14.2	Percent hydrogen	5.5
HV: 7695 Btu/lb		Percent nitrogen	0.22
(17,898 KJ/kg)		Percent chlorine	0.23
		Percent sulfur	0.70
		Percent oxygen	33.9
		(by diff.)	

<u>Americology RDF</u>			
<u>Proximate</u>		<u>Ultimate</u>	
Percent moisture	9.5	Percent moisture	9.5
Percent ash	13.2	Percent ash	13.2
Percent volatile	68.1	Percent carbon	46.2
Percent fixed carbon	9.2	Percent hydrogen	6.2
HV: 7837 Btu/lb		Percent nitrogen	0.62
(18,228 KJ/Kg)		Percent chlorine	0.50
		Percent sulfur	0.32
		Percent oxygen	23.5
		(by diff.)	

TABLE 3. TRACE METALS ANALYSIS OF FUELS
ppm wt as determined by spark
source mass spectroscopic

Element	Fuel Type		
	Coal	Eco-Fuel II	Americology
Uranium	< 2.00E+0	< 2.00E+0	< 6.00E+0
Thorium	< 4.00E+0	< 4.00E+0	< 1.20E+1
Bismuth	< 2.00E+0	< 2.00E+0	< 6.00E+0
Lead	< 4.00E+0	4.00E+1	6.00E+2
Thallium	< 4.00E+0	< 4.00E+0	< 8.00E+0
Mercury	< 6.00E+1	< 6.00E+1	< 1.00E+2
Gold	< 1.00E+0	< 1.00E+0	< 4.00E+0
Platinum	< 2.00E+0	< 2.00E+0	< 4.00E+0
Iridium	< 2.00E+0	< 2.00E+0	< 6.00E+0
Osmium	< 2.00E+0	< 2.00E+0	< 1.00E+1
Rhenium	< 2.00E+0	< 2.00E+0	< 6.00E+0
Tungsten	< 2.00E+0	< 2.00E+0	< 1.00E+1
Tantalum	< 1.00E+1	< 1.00E+1	< 2.00E+1
Hafnium	< 2.00E+0	< 2.00E+0	< 1.00E+1
Lutecium	< 1.00E+0	< 1.00E+0	< 2.00E+0
Ytterbium	< 2.00E+0	< 2.00E+0	< 1.00E+1
Thulium	< 1.00E+0	< 1.00E+0	< 2.00E+0
Erbium	< 2.00E+0	< 2.00E+0	< 1.00E+1
Holmium	< 1.00E+0	< 1.00E+0	< 2.00E+0
Dysprosium	< 2.00E+0	< 2.00E+0	< 1.00E+1
Terbium	< 6.00E-1	< 6.00E-1	< 2.00E+0
Gadolinium	< 2.00E+0	< 2.00E+0	< 1.00E+1
Europium	< 2.00E+0	< 2.00E+0	< 6.00E+0
Samarium	< 2.00E+0	< 2.00E+0	< 1.00E+1
Neodymium	< 4.00E+0	4.00E+0	< 2.00E+1
Praseodymium	< 6.00E-1	6.00E-1	< 2.00E+0
Cerium	< 3.00E-1	2.00E+0	2.00E+0
Lanthanum	< 6.00E-1	4.00E+0	6.00E-1
Barium	2.00E+1	6.00E+2	4.00E+2
Caesium	< 9.00E-1	< 9.00E-1	< 3.00E-1
Iodine	< 2.10E+0	< 9.00E-1	< 3.00E+0
Tellurium	< 2.00E+0	< 2.00E+0	< 6.00E+0
Antimony	< 6.00E+0	< 6.00E+0	< 6.00E+0
Tin	< 2.00E+0	< 6.00E+0	< 1.00E+1
Indium	< 3.00E-1	< 3.00E-1	< 2.00E+0
Cadmium	< 6.00E+0	< 6.00E+0	< 1.80E+1
Silver	< 3.00E-1	< 3.00E-1	< 1.20E+0
Palladium	< 2.00E+0	< 2.00E+0	< 6.00E+0
Rhodium	< 6.00E-1	< 6.00E-1	< 2.00E+0
Ruthenium	< 2.00E+0	< 2.00E+0	< 6.00E+0
Molybdenum	< 2.00E+0	< 1.00E+0	< 3.00E+0
Niobium	< 4.00E+0	< 4.00E+0	< 2.00E+0
Zirconium	1.00E+0	1.00E+1	1.00E+1

TABLE 3 (continued)

Element	Fuel Type		
	Coal	Eco-Fuel II	Americology
Yttrium	2.00E+0	4.00E+0	< 2.00E+0
Strontium	8.00E+0	8.00E+1	8.00E+1
Rubidium	< 1.20E+0	< 1.20E+0	< 4.00E+0
Bromine	5.00E+0	2.50E+0	1.50E+2
Selenium	< 7.00E-1	< 1.40E+0	< 1.40E+0
Arsenic	2.00E-1	2.00E+0	5.00E+0
Germanium	< 1.00E+0	< 1.00E+0	< 4.00E+0
Gallium	1.00E+0	< 3.00E+0	< 3.00E+0
Zinc	2.00E+0	6.00E+1	2.00E+2
Copper	5.00E+0	3.00E+2	5.00E+2
Nickel	5.00E+0	2.00E+2	5.00E+1
Cobalt	1.00E+1	1.00E+0	< 1.00E+0
Iron	4.19E+2	1.32E+4	6.00E+3
Manganese	5.10E-1	9.00E+2	9.00E+2
Chromium	6.00E-1	6.00E+1	6.00E+1
Vanadium	6.00E+0	1.20E+1	1.20E+1
Titanium	5.00E+1	2.00E+3	2.00E+3
Scandium	< 4.00E+0	< 4.00E+0	< 4.00E+0
Calcium	9.99E+2	3.00E+4	1.00E+5
Potassium	3.99E+1	2.00E+4	2.00E+4
Chlorine	3.40E+1	3.94E+2	3.99E+3
Sulphur	1.40E+3	6.00E+3	2.00E+3
Phosphorus	8.00E+0	4.00E+2	8.00E+2
Silicon	1.47E+3	6.00E+4	9.00E+4
Aluminum	8.99E+2	5.99E+3	5.99E+3
Magnesium	1.00E+2	2.00E+3	2.00E+3
Sodium	2.99E+2	1.20E+4	1.20E+4
Fluorine	< 4.00E+0	4.00E+0	1.20E+1
Boron	5.99E+1	2.99E+1	2.99E+1
Beryllium	2.00E+0	2.00E-2	< 5.00E-2
Lithium	1.20E+0	3.00E+0	1.20E+1

TABLE 4. TOXIC METALS ANALYSIS OF FUELS
 $\mu\text{g/g}$ determined by atomic absorption
 spectroscopy

Chemical Species	Fuel		
	Coal	Eco-Fuel II RDF	Americology RDF
Mercury	0.17	0.78	2.0
Arsenic	0.42	0.10	1.4
Antimony	<1.0	<1.0	6.0
Lead	1.0	72.0	325
Tellurium	<1.0	<1.0	2.0
Beryllium	1.4	<0.1	<0.1

spectroscopy analysis (AAS) of the fuels for toxic metals. Significant differences between the fuels are:

- Higher concentrations of lead in the refuse. The coal, Eco-Fuel II and Americology contain 1 $\mu\text{g/g}$; 72 $\mu\text{g/g}$ and 325 $\mu\text{g/gm}$, respectively.
- Higher concentrations of copper, nickel, iron, manganese, calcium, potassium, magnesium, silicon and sodium are found in the refuse (see Table 3).
- Lower concentrations of aluminum are found in the refuse relative to the concentrations found in the coal (see Table 3).

ECO-FUEL II

The Eco-Fuel II is a granular material, dark green in appearance. Approximately 75 percent of the material is less than 88 microns in size (200 mesh).

The RDF was pelletized by Battelle to enhance the grate burning characteristics and to minimize particle carryover caused by the overfire air jets within the boiler firebox.

The Eco-Fuel II was an easily handled and easily pelletized material compared to the shredded Americology RDF or other shredded biomass materials. We experienced no difficulties in feeding the material into a pelletizer, and the pellets that were formed were strong and did not degrade with time or with changes in laboratory ambient air conditions (high or low humidity, high or low temperatures, etc.).

This material was obtained from Combustion Equipment Associates, Inc., from their East Bridgewater, Mass., processing plant.

AMERICOLOGY

The Americology RDF that was supplied to Battelle was significantly different from the Eco-Fuel II. The Americology was a shredded material from a commercial refuse processing plant. The size of material ranged from 1-1/2 inch to 3-inches or more.

Because the RDF was comprised of large pieces of material compared to the pellets, it was necessary for the RDF to be shredded again by Battelle in a small, high-speed hammermill. The hammermill shredder screen was perforated with 1/8-inch holes, thus limiting the maximum RDF size to

1/8-inch. The shredding process was a rather slow one, requiring several weeks to shred one ton of RDF in the laboratory bench facility. However, the pelletization process was even slower than the shredding, requiring several months to pelletize enough RDF for the program. Also, the Americology RDF was not free flowing and was abrasive. The equipment repeatedly jammed while pelletizing this RDF, and there was noticeable wear on close tolerance shafts and bearings.

The Americology pellets did degrade with time, and supported growths of some type of fungus on the pellets after several months in storage.

In at least one instance a drum of Americology spontaneously ignited at our processing facility. At a later date, investigation of other drums of pelletized RDF found temperatures as high as 160 F in the center of several drums. To minimize the possibility of a second occurrence of spontaneous ignition, all of the original containers were emptied and the fuel divided into smaller containers. Dividing up the fuel pellets into smaller quantities increased the surface area to volume ratio and decreased the internal temperatures of the barrel through enhanced heat loss.

This material was obtained from the Americology Division of American Can Co., from their processing plant in Milwaukee, Wisconsin.

COAL

The coal supplied to Battelle was from eastern Kentucky and is considered to be a high quality stoker coal. The coal was double screened (1/4 by 1-1/4), washed, and oil treated for dust control. The heating value of the fuel (as received) was approximately 12,500 Btu/lb (see Table 2).

HAZARDOUS WASTE

Triethanolamine was selected as the hazardous material to be used in this study. This choice was for the following reasons:

- The material was classified as a hazardous material, yet suitable for laboratory handling and burning.

- It was a liquid at or near room temperature and it exhibited a low vapor pressure. This made it easy to handle and did not require special equipment for the personnel involved.
- The hazardous material was comprised only of C, H, O and N, hence, there are no elemental products of combustion that can be considered as hazardous or toxic.

This material is used in detergents and as a corrosion inhibitor. It is a colorless liquid with a melting point of 21 C (70 F) and a boiling point of 335 C (635 F). It is hygroscopic with a specific gravity slightly greater than water and a viscosity of 600 mPa at 25 C.

The triethanolamine was mixed with water (2:1 by weight in the first experiment and 1:2 weight in the second) and then added to the Eco-Fuel II prior to pelletization.

Table 5 shows the ultimate analysis of the combined fuel fired during each test, calculated from the weight fractions of the separate fuels cofired during the test. Also shown are the calculated heating values of the combined fuels.

TABLE 5. INTEGRATED FUEL CHEMICAL COMPOSITION

Chemical Species	Test Number						
	1	2	3	4	5	6(b)	7(c)
Major Constituents in Weight Percent							
C	70.34	50.02	43.80	55.50	46.20	54.29	54.19
H	4.62	5.16	5.50	5.60	6.20	5.29	5.20
O	8.52	24.10	33.90	17.73	23.50	23.01	23.51
N	1.28	0.63	0.22	0.87	0.62	1.10	0.88
S	1.30	0.93	0.70	0.70	0.32	0.91	0.92
Cl	0.08	0.17	0.23	0.34	0.50	0.17	0.17
Ash	8.78	9.53	10.0	11.50	13.2	9.16	9.41
H ₂ O	5.08	5.40	5.60	7.80	9.50	6.09	5.72
Toxic Metals in ppm							
Hg	0.17	.54	0.78	1.3	2.0	.53	.54
As	0.42	.22	0.10	1.0	1.4	.23	.23
Sb	<1.0	<.10	<1.0	<4.0	6.0	<1.0	<1.0
Pb	1.0	45	72	200	325	43	44
Te	<1.0	<1	<1.0	1.6	2.0	<1.0	<1.0
Be	1.4	<.60	<0.1	<0.60	<0.1	<.63	<.62
Heating Value (a)							
Btu/lb	12484	9540	7695	9626	7837	9525	9530
(kJ/Kg)	(29036)	(22190)	(17900)	(22390)	(18230)	(22157)	(22168)

(a) On an as fired basis

(b) Contains triethanolamine, 10 wt % of the RDF pellet

(c) Contains triethanolamine, 5 wt % of the RDF pellet

SECTION 7

EXPERIMENTAL BURNING PROGRAM

Emission measurements and samples were collected during seven tests. In each test the fuel firing rate was approximately 500,000 Btu/hr, with a minimum practical oxygen level in the flue gas. This firing rate is equivalent to about a 62 percent of boiler capacity. A higher firing rate was not used because the ash bed would build up too rapidly during the all-refuse experiments.

The minimum excess air was determined by identifying at what level incomplete combustion became significant. It was found that when flue gas oxygen concentration dropped below 5 percent, large quantities of smoke and high CO concentrations were emitted, even while using the overfire air jets to improve combustion efficiency.

The emission sampling that was performed for each test is listed in Table 6. All of the tests were monitored by continuous gas analyzers and were sampled by the SASS train according to Level One procedures.

In addition batch samples of the flue gases were taken in tests 6 and 7 (experiments in which the hazardous waste was used) and analyzed for total NO_x concentrations by a wet chemical method. This procedure was used to corroborate information obtained from other instruments on the concentrations of NO_x in the stack. Flue gas samples from all seven tests were analyzed for NH_4 ($i=1,3$) levels and cyanide levels. This was necessary so that other forms of nitrogen containing species could be isolated and comparisons made between those tests that did not contain the waste chemical and those experiments that did.

Also, the stack gases were analyzed for chlorides and fluorides, since these species are present in the refuse. The last test was not monitored for these two species since the last experiment was a repeat of Experiments 2 and 6. For the first six tests the stack gases were analyzed for sulfur compounds (H_2S , COS ...) and hydrocarbons $\text{C}_1\text{-C}_7$. The final test was not monitored for these species because it was felt that this would be redundant.

TABLE 6. EXPERIMENTAL SAMPLING MATRIX

Monitoring/ Sampling Techniques	Test Number Run						
	1	2	3	4	5	6	7
	C	C+E	E	C+A	A	C+E+HW(I)	E+HW(II)
CO ₂	X	X	X	X	X	X	X
O ₂	X	X	X	X	X	X	X
CO	X	X	X	X	X	X	X
SO ₂	X	X	X	X	X	X	X
NO	X	X	X	X	X	X	X
THC	X	X	X	X	X	X	X
SASS Sampling	X	X	X	X	X	X	X
Method 7 (NO _x)						X	X
Cyanides	X	X	X	X	X	X	X
Cl	X	X	X	X	X	X	
F	X	X	X	X	X	X	
NH ₃ (1 = 1→3)	X	X	X	X	X	X	X
H ₂ S	X	X	X	X	X	X	
C ₁ -C ₇	X	X	X	X	X	X	

C - Coal only

C+E - Coal + Eco-Fuel II

E - Eco-Fuel II Only

C+A - Coal + Americology

A - Americology only

C+E+HW(I) - Coal + Eco-Fuel II + Hazardous Waste, 10 wt percent

C+E+HW(II) - Coal + Eco-Fuel II + Hazardous Waste, 5 wt percent

SAMPLING/MONITORING EQUIPMENT AND PROCEDURES

The following list contains the apparatus used to monitor and control the 7 tests.

CO ₂ analyzer:	Beckman Model 864
CO analyzer:	Beckman Model 864
O ₂ analyzer:	Taylor OA-272
NO _x analyzer:	Beckman Model 315B-NDIR (used in all experiments) Beckman Model 955-chemiluminescence (used in Experiments 5 and 7)
SO ₂ analyzer:	Faristor Type
THC analyzer:	Beckman Model 402
C ₁ -C ₃ Hydrocarbons:	Varian FID/GC
C ₄ -C ₇ Hydrocarbons:	Varian FID/GC
H ₂ S, SO ₂ :	Hewlett Packard FPD/GC

The gaseous and particulate material in the flue gases were sampled as follows:

- Source Assessment Sampling System (SASS)
- Method 7 (for additional NO_x species determinations)
- Method 6 (a modified method that was used to sample for Cl, CN, NH₃ and F).

Additional analyses were performed on flue gas samples by mass spectrometer. The information obtained from the MS results were used as a further check on results obtained by other methods (such as continuous analyzers).

To prevent condensation in the sampling line, a heated stainless steel line was used to extract gas samples. Also, a method of cross checking data was utilized to assure that the sample line was not leaking or condensing flue gas material. One method of checking was to sample the flue gases for SO₂ at the stack (see Figure 3) and to then sample the flue gases at the termination point of the sampling line. The SO₂ determinations made with the Varian Model 3700 FPD-GC always compared favorably with results obtained from the Faristor electrochemical SO₂ monitor. This indicated that the sampling system was secure and non-condensing.

TEMPERATURE MONITORING

The light lines on Figure 3 indicate the locations of most of the thermocouples used to monitor the stoker. The thermocouples were placed at the following locations:

- Thermocouple 50 - stack at the point where the SASS train was located
- Thermocouple 51 - breaching
- Thermocouple 52 - cold water feed to the boiler
- Thermocouple 53 - hot water outlet from the boiler
- Thermocouple 54 - boiler reservoir water temperature
- Thermocouple 55-57 - combustion chamber inside the boiler 22 inches above the grate.

After completing the first three tests it was decided to place two additional thermocouples in the burning bed of fuel. Therefore, an additional thermocouple was placed near the center of the combustion chamber, 4 inches above the grate, and another thermocouple was placed 8 inches above the grate. Other bed temperature measurements were made by using an optical pyrometer.

QUALITY CONTROL/QUALITY ASSURANCE

Extensive efforts were made to ensure a high reliability of the data and specimens collected. The techniques that were utilized in our quality assurance program were as follows:

- All gas standards were analyzed and documented prior to use
- Gas samples were analyzed by a variety of techniques as a means of cross checking. Some of the sampling techniques utilized were NDIR, chemiluminescent, colorimetric, orsat, gas chromatograph and mass spectrometer
- Standard gases were passed through the entire gas sampling system to assure the integrity of the sampling system
- Gas analyzers were calibrated before, during and after an experiment
- Samples of particulates and gases that were submitted for chemical analysis were coded so as not to identify the real samples from the blanks or spiked ones
- Standards solutions and solvents that were utilized were of the highest purity available
- All laboratory glassware was thoroughly cleaned and dried
- All preparation areas were cleaned before and after use
- All equipment or utensils used to handle components of the sampling system were cleaned prior to use
- All personnel were aware of the sampling requirements and special precautions were taken to avoid any sample contamination (e.g. light exposure, accidental exposure to room dust, etc.)

SECTION 8

EXPERIMENTAL RESULTS

OPERATING CHARACTERISTICS OF THE BOILER

As was indicated earlier, it was desired that all of the tests be conducted while operating the boiler under the following conditions:

- Boiler fired at 500,000 Btu/hr (527,500 kJ/hr)
- Lowest O₂ levels in the stack consistent with clean burning (8-10 percent)

After completing the test program an analysis of the boiler operation conditions for all seven tests indicated that the average operating conditions were:

- Average firing rate: 519,300 Btu/hr (547,860 kJ/hr)
- Average stack O₂ level (dry): 11.7 percent (approximately 100 percent excess air)

DIRECT ANALYSES OF EMISSION STREAMS

Table 7 shows the experimental test conditions as measured during the test runs. These data represent the averages of readings taken from the continuous monitors every 5 minutes throughout the test runs lasting over 5 hours. The CO and total hydrocarbon measurements averaged less than 20 ppm for all tests.

As evidenced by the very low CO levels, fuel combustion was considered complete. Overall, the flue gases may be considered fairly clean, comprising very little CO and unburned hydrocarbons. However, short term instabilities were observed during normal boiler operations. These instabilities arose when the fuel feed system jammed or when it accidentally overfed the boiler. When these occurred the CO concentration rose above 5000 ppm for a short time accompanied by excursions in the O₂ concentration.

TABLE 7. EXPERIMENTAL CONDITIONS

Test Number	Coal Feed lb/hr (kg/hr)	RDF Type	RDF Feed lb/hr (kg/hr)	Air Feed lb/hr (kg/hr)	Heat Input 10 ⁶ Btu/hr (10 ⁶ kJ/hr)	Stack Temp., F (C)	Comb. Temp., F (C)	Bed (a) Temp., F (C)	Water (b) Temp., F (C)	CO ₂ Percent (Dry)	SO ₂ PPM Electrochemical Cell	NO _x PPM NDIR	Excess Air, percent	Bed Temp., F Optical Pyrometer
1.	37.8 (17.1)	-	-	679 (308)	.472 (.497)	450 (232)	1899 (1037)	-	177 (80.2)	8.5	428	200	87	
2.	23.2 (10.5)	E	37.1 (16.8)	1197 (543)	.575 (.606)	506 (263)	1989 (1087)	-	175 (79.4)	9.44	396	175	82	
3.	-	E	71.7 (32.5)	906 (411)	.552 (.582)	466 (241)	1906 (1041)	-	161 (71.6)	8.50	295	170	128	
4.	21.9 (9.95)	A	35.1 (15.9)	1205 (546)	.548 (.578)	520 (271)	1906 (1041)	1850 (1010)	174 (78.9)	4.9	225	150	177	2000
5.	-	A	64.9 (29.4)	977 (443)	.549 (.537)	450 (232)	1870 (1021)	2148 (1176)	173 (78.3)	8.50	50	220	132	2050
6.	21.0 (9.53)	E+HW (1)	33.6 (15.2)	648 (294)	.525 (.554)	457 (236)	1662 (905)	1962 (1072)	183 (83.9)	8.67	373	260	107	1800
7.	20.0 (9.07)	E+HW (11)	32.0 (14.5)	569 (258)	.500 (.528)	523 (273)	2559 (1403)	2089 (1143)	187 (86.1)	9.67	412	250	94	

(a) Highest values recorded by thermocouples

(b) Water outlet from boiler

(c) Gases above bed, highest temperature observed

E - Eco-Fuel II

A - Americology

E+HW(1)-Eco-Fuel II + hazardous waste, 10 wt%

E+HW(11)-Eco-Fuel II + hazardous waste, 5 wt%

The first test, burning only the coal, constitutes the baseline with which the next 6 tests can be compared. This operation is considered representative of a conventional spreader-stoker burning of coal in small industrial boilers.

Sulfur Emissions

Table 8 indicates the sulfur balance for the seven tests. An SO₂ stack sample was collected with the Method 6 impinger and titrated to determine the SO₂ content. This single analysis was thus an integrated sample representing the entire sampling period. Samples were also obtained during the test run for analysis of SO₂ by gas chromatography and by the Faristor analyzer. Table 8 compares the emissions as measured by those three techniques. The variability of the GC analyses of SO₂ content of the flue gas was supported by the non-uniformity of the combustion as recorded by the continuous monitors of stack gas composition.

As evidenced in Table 8 a complete sulfur balance was achieved only in Test 3 and 4. In the remaining tests approximately 18-49 percent of the sulfur is unaccounted for. This sulfur "loss" cannot be attributed to flaws in the flue gas analysis because 3 different SO₂ measurement techniques were utilized. All SO₂ measurement techniques failed to provide a favorable sulfur balance for the tests with a high level of SO₂ unaccounted for. This problem may have been caused by several factors including:

- analysis of sulfur in fuel was not representative of entire fuel supply
- variability in fuel sulfur content of material entering the furnace
- variability of fuel firing rate
- a combination of the above.

Nitrogen Emissions

Table 9 shows the nitrogen emission data as determined by fuel nitrogen content and NDIR analysis of the flue gas. Assuming that all the nitrogen in the NO in the stack gas resulted from fuel nitrogen, approximately one quarter of the fuel nitrogen was converted to NO in this boiler when

TABLE 8. SULFUR EMISSION DATA

	Test Number						
	1	2	3	4	5	6	7
Sulfur in fuel, wt %	1.30	0.93	0.70	0.70	0.32	0.91	0.92
Input feed rate lb/hr	0.49	0.56	0.50	0.40	0.21	0.50	0.47
(kg/hr)	(0.22)	(0.25)	(0.23)	(0.18)	(0.094)	(0.22)	(0.22)
SO ₂ In Stack, ppm ^(a)	477	462	403	271	98	394	388
Stack Sulfur Emission Rate							
lb/hr	0.39	0.46	0.50	0.40	0.16	0.29	0.24
(kg/hr)	(0.18)	(0.20)	(0.23)	(0.18)	(0.071)	(0.13)	(0.11)
wt percent leaving							
stack as SO ₂	82	80	100	100	76	58	51
SO ₂ in Stack, ppm ^(b)	428	396	295	225	50	373	412
SO ₂ in Stack, ppm ^(c)							
	428	218	220	287	78	282	251
	420	230	(d)	159	81	(d)	ND
	492	283	260	265	97	274	248
		329	203	190	97	265	344
		315	214	206	88	(d)	251
			311	273	93	251	272
			324	154	350	299	
				178	100	292	
				217	97		
				170	109		
					98		
					78		

(a) As measured by method 6 techniques

(b) As measured by on-line monitor, averaged over test run

(c) As measured by GC/FID of grab samples

(d) Duplicate analysis of same sample

ND = Not determined

TABLE 9. NITROGEN EMISSION DATA

	Test Number						
	1	2	3	4	5	6	7
N content of fuel, wt %	1.28	0.63	0.22	0.87	0.62	1.10	0.88
Input feed rate lb/hr	0.48	0.38	0.16	0.50	0.40	0.60	0.46
(kg/tr)	(0.22)	(0.17)	(0.072)	(0.23)	(0.18)	(0.27)	(0.21)
NO in stack, ppm (a)	200	175	170	150	220	260	250
N emission rate (b)							
lb/hr	0.11	0.098	0.122	0.130	0.17	0.13	0.11
(kg/hr)	(0.050)	(0.044)	(0.055)	(0.059)	(0.078)	(0.061)	(0.050)
wt percent leaving stack							
stack as NO(c)	23	26	76	26	43	23	24
(a) Measured by NDIR monitor	Run 1 - Coal only						
(b) N in NO	Run 2 - Coal + Eco-Fuel II						
(c) relative to the fuel nitrogen input	Run 3 - Eco-Fuel II only						
	Run 4 - Coal + Americology						
	Run 5 - Americology only						
	Run 6 - Coal + Eco-Fuel II + Hazardous waste, 10 percent						
	Run 7 - Coal + Eco-Fuel II + Hazardous waste, 5 wt percent						

burning coal or when cofiring coal and RDF. When firing RDF only, with its reduced nitrogen content, the conversion efficiencies increased. These observations are in general agreement with fuel nitrogen conversion efficiencies typical of fossil fuel burning, including the observed increase in conversion efficiency at lower fuel nitrogen content.⁽⁴⁾

The NO concentrations measured in this program when cofiring coal and pelletized RDF (150 to 175 ppm) are slightly higher than those observed in English boiler tests⁽⁵⁾ (132 to 140 ppm) and lower than those observed in other U.S. tests⁽⁶⁾ (200 to 350) ppm. The NO emissions appear to be dependent on the total combined nitrogen in the fuel and on the boiler conditions, rather than any other characteristic of the RDF.

During the last two tests in which several different techniques were used to determine the NO_x levels in the stack, somewhat higher NO_x levels are recorded by the nondispersive infrared (NDIR) technique with different concentrations of NO_x recorded by the other measurement methods. In test 6 the chemiluminescent method agrees quite well with NDIR measurement, although neither the mass spectrometer technique nor the colorimetric technique agree with the first two measurements:

- 260 ppm by NDIR
- 250 ppm by chemiluminescence
- 135 ppm by mass spectrometry of a single grab sample
- 163 ppm by wet colorimetric technique for two grab samples

The addition of the amine in tests 6 and 7 increased the nitrogen content of the fuel appreciably over that burned in the comparable test 2. Although the total emissions of NO were increased, the conversion efficiency was essentially unchanged.

Chloride Emissions

Table 10 shows the chloride emissions from the stack. Not only was the chlorine content of the Americology RDF higher than in the coal and the Eco Fuel II, but the carry-thru of chlorine to chlorides in the flue gas from the Americology was also apparently more complete as indicated by the simple mass balance shown on the table.

TABLE 10. CHLORIDE EMISSION DATA

	Test Number				
	1	2	3	4	5
Cl content of fuel, wt%	0.08	0.17	0.23	0.34	0.50
Input feed rate, lb/hr	0.03	0.10	0.16	0.19	0.32
(kg/hr)	(0.014)	(0.046)	(0.075)	(0.088)	(0.15)
Cl-emissions (gaseous)					
lb/hr	0.011	0.067	0.016	0.196	0.335
(g/hr)	(5.0)	(30.0)	(7.3)	(89.0)	(152)
lb/10 ⁶ Btu	0.0235	0.115	0.030	0.357	0.535
ng/J	(0.101)	(0.496)	(0.129)	(1.54)	(2.31)
PPM	12.6	67.4	12.0	115	245
Percent chloride accounted for in stack	37	67	10	100	100

A large amount of the chlorine in the first three tests remains unaccounted for. It is suggested that the missing chlorine can be retained:

- in the particulate matter
- in the bed ash
- on the interior surfaces of the boiler.

The analytical results shown later indicate that approximately 1-2 percent of the total chlorine was contained in the particulate matter. The samples that were analyzed in these cases were taken from the firetubes of the boiler and not from cyclones or filter of the SASS train, although the chemical compositions are probably similar. Analysis of the bottom ash taken from the second test (coal and Eco-Fuel II) indicates that there was very little chlorine remaining in the bed. This leaves a significant part of the chlorine still unaccounted for. It is reasonable to assume that some of the unaccounted chlorine became chemically bound to the boiler's interior surface. Previous studies have found the chlorides in the presence of sulfur containing compounds (such as SO_2) can chemically react with hot metal surfaces, such as those found inside a boiler⁽⁷⁻¹²⁾. The evidence of this chemical reaction is the corrosion observed on the interior metal surfaces of the boiler. The presence of these chlorine compounds in the combustion system is believed responsible for metal wastage and fatigue observed in municipal incinerators and in power plants. In this study, evidence of severe chemical attack on the overfire air jets was noted during the third test, and examination of the jets after that test indicated that they had been extensively corroded. After these jets had failed, a new set was installed which lasted for the remainder of the program.

It is interesting to note that severe metal wastage of the over-fire air jets was experienced in those experiments in which a large quantity of the chlorine was unaccounted for. Although some metal wastage also occurred after a new set of jets was installed, the new set exhibited greater survivability during the subsequent tests in which nearly all of the chlorine was accounted for in the stack.

Suspended Particulates

The particulate loadings in the stack when cofiring RDF with coal were higher than when burning coal only as shown on Table 11. The three runs with Eco Fuel II cofired with coal (Tests 2, 6, and 7) had loading increases of 15 to 40 percent over the CO₂-corrected loading when burning only coal. The cofiring of Americology RDF resulted in over twice the particulate loading from coal-only burning. When the RDFs were burned without coal, the Americology (Test 5) again resulted in higher particulate emissions than the Eco Fuel II (Test 3). These differences in the particulate emissions may result from the stronger cohesive bonding of the Eco Fuel pellets, which resulted in the burned and partially burned fragments being retained within the bed. The Americology pellets broke up more extensively during the feeding and burning, resulting in a larger mechanical carry-over of fragments from the bed.

The suspended particulate emissions observed in an English test burning densified RDF and coal in an industrial boiler were about one half the mass concentration measured in this program⁽⁵⁾. Conversely the cofiring of shredded RDF (not pelletized) with coal in other Battelle boiler tests conducted in a large spreader-stoker boiler installation resulted in emissions greater than in these tests by more than an order of magnitude⁽¹¹⁾.

The size distribution of the suspended particulates as shown in Table 12 indicates that the RDF burning produced a higher fraction of respirable sizes in the total particulate emissions. Whereas about 30 percent of the particulates from coal were below 3 μ m in size, more than 80 percent of the particulates from RDF-only burning were in this size range. As would be expected the cofiring tests resulted in an intermediate fraction of particulate mass in this small size range.

Fire Tube Deposits

After each test particulate matter that had collected in the fire-tubes of the boiler was removed, although an analysis was performed only on the material collected from the first three tests. The analyses include proximate, ultimate, and trace materials, and are presented in Tables 13-15.

TABLE 11. PARTICULATE EMISSION DATA

	Test Number						
	1	2	3	4	5	6	7
Fuel Feed lb/hr	37.8 (17.1)	60.3 (27.3)	71.7 (32.5)	57 (25.9)	64.9 (29.4)	54.6 (24.8)	52 (23.6)
A/F ratio	9.44	7.04	5.54	7.63	6.50	7.04	7.04
Percent Excess Air	87.0	82.0	128	176	132	107	94.4
Stack Temp F	450	506	466	521	450	457	523
Stack Temp (C)	(232)	(263)	(241)	(272)	(232)	(236)	(273)
Stack Gas Velocity - fpm	261	326	360	503	378	250	247
(M/min)	(79.6)	(99.4)	(110)	(153)	(115)	(76.2)	(75.3)
Volume of Gas Sampled - ft ³	1206	1164	1180	1166	1206	1230	1171
(m ³)	(34.1)	33.0	33.4	33.0	34.2	34.8	33.2
Weight of sample - grains	53.78	62.69	37.36	111.4	145.7	68.2	78.40
(milligrams)	(3485)	(4063)	(2421)	(7219)	(9441)	(4419)	(5080)
Dry gas volumetric flow							
at 68 F and 29.92 in Hg	8853	10285	12040	15602	12908	8622	7730
ft ³ /hr							
Dry gas volumetric flow at							
1 ATM and 20 C (M ³ /hr)	(250.7)	(291.3)	(341.0)	(441.9)	(365.5)	(244.2)	(219.0)
Particulate Loading							
Grains/SCF (a)	0.0479	0.0574	0.343	0.106	0.129	0.0587	.0723
Grains/SCF (b)	0.0632	0.0730	0.0484	.141	0.182	0.0812	.0899
(mg/M ³) (c)	145	(167)	(111)	(323)	(417)	(186)	(206)
Mass Emission Rate							
#/hr	0.061	0.084	0.059	0.236	0.240	0.0723	.0801
(G/hr)	(27)	(38)	(27)	(107)	(108.2)	(32.80)	(36.30)
lb/10 ⁶ Btu	0.128	0.146	0.107	0.429	.469	0.139	0.157
(ng/J)	(0.0552)	(0.0628)	(0.0451)	(0.185)	(0.202)	(0.0599)	(0.0698)

(a) at the measured CO₂ level(b) at 12 percent CO₂, 68 F and 29.92 in Hg(c) at 12 percent CO₂, 20 C and 1 ATM

TABLE 12. PARTICULATE SIZE DISTRIBUTION
(all weights are in milligrams)

Location	Test Number						
	1	2	3	4	5	6	7
Probe Nozzle Wash (percent of total)	107.1 (3.1)	423.0 (10.4)	100.1 (4.1)	411.5 (5.7)	473.7 (5.0)	267.1 (6.0)	443.3 (8.7)
10 μ cyclone (percent of total)	1400 (40.2)	1550 (38.1)	240 (9.9)	1020 (14.1)	305.9 (3.2)	1080 (24.4)	932.4 (18.4)
3 μ cyclone (percent of total)	900 (25.8)	110 (2.7)	50 (2.1)	510 (7.1)	188.6 (2.0)	510 (11.5)	455.9 (9.0)
1 μ cyclone (percent of total)	380 (10.9)	0 (0)	16.5 (0.7)	130 (1.8)	495.3 (5.2)	100 (2.3)	76.8 (1.5)
filter catch (percent of total)	698 (20.0)	1980 (48.8)	2014.6 (83.2)	5147.8 (71.3)	7977.7 (84.6)	2461.5 (55.8)	3171.3 (62.4)
Total Particulate Catch	3485.1	4063.4	2421.2	7219.3	9441.3	4418.6	5079.7

Hazardous waste comprises 10 Wt percent of the fuel pellet in run 6
Hazardous waste comprises 5 Wt percent of the fuel pellet in run 7

TABLE 13. FIRE TUBE FLY ASH CHEMICAL ANALYSIS -
TEST 1, COAL(a)

PROXIMATE ANALYSIS			ULTIMATE ANALYSIS		
	As Rec'd.	Dry Basis		As Rec'd	Dry Basis
%Moisture	3.33	xxxxx	%Moisture	3.33	xxxxx
%Ash	48.95	50.64	%Carbon	37.82	39.12
%Volatile	16.24	16.80	%Hydrogen	0.62	0.64
% Fixed Carbon	31.48	32.56	%Nitrogen	0.37	0.38
	100.00	100.00	%Chlorine	0.04	0.04
Btu/lb.	5467	5655	%Sulfur	2.10	2.17
%Sulfur	2.10	2.17	%Ash	48.95	50.64
			%Oxygen (diff)	6.77	7.01
				100.00	100.00

TRACE ELEMENTS					
ELEMENT	CONC. PPM WT.	ELEMENT	CONC. PPM WT.	ELEMENT	CONC. PPM WT.
Uranium	12	Gadolinium	4	Yttrium	62
Thorium	14	Europium	2	Strontium	160
Bismuth	3	Samarium	7	Rubidium	66
Lead	310	Neodymium	21	Bromine	52
Thallium	36	Praseodymium	10	Selenium	41
Mercury*	0.83	Cerium	44	Arsenic	MC
Gold		Lanthanum	63	Germanium	76
Platinum		Radium	810	Gallium	250
Tridium		Cesium	5	Zinc	MC
Osmium		Iodine	16	Copper	680
Rhenium		Tellurium		Nickel	140
Tungsten	4	Antimony	26	Cobalt	26
Tantalum	<0.3	Tin	17	Manganese	260
Hafnium	0.8	Cadmium	6	Chromium	38
Lutetium	0.4	Silver	3	Vanadium	380
Ytterbium	2	Palladium		Scandium	4
Thulium	0.2	Rhodium		Fluorine**	≈110
Erbium	0.7	Ruthenium		Boron	32
Holmium	2	Molybdenum	38	Beryllium	3
Dysprosium	4	Niobium	17	Lithium	71
Terbium	1	Zirconium	120		

All elements not reported < 0.1 ppm weight

*Flameless Atomic Absorption

**Specific Ion Electrode

(a) Determinations by Commercial Testing and Engineering Co., Chicago, Illinois. Trace Elements obtained by Spark Source Mass Spectrometry.

TABLE 14. FIRETUBE FLY ASH CHEMICAL ANALYSIS -
TEST 2, COAL + ECO-FUEL II(a)

PROXIMATE ANALYSIS			ULTIMATE ANALYSIS		
	As Rec'd.	Dry Basis		As Rec'd	Dry Basis
%Moisture	1.39	xxxxx	%Moisture	1.39	xxxxx
%Ash	45.67	46.31	%Carbon	47.19	47.86
%Volatile	10.42	10.57	%Hydrogen	0.53	0.54
% Fixed Carbon	42.52	43.12	%Nitrogen	0.64	0.65
	100.00	100.00	%Chlorine	0.40	0.41
Btu/lb.	6885	6982	%Sulfur	1.80	1.83
%Sulfur	1.80	1.83	%Ash	45.67	46.31
			%Oxygen (diff)	2.38	2.40
				100.00	100.00

ELEMENT		TRACE ELEMENTS		ELEMENT	
	CONC. PPM WT.		CONC. PPM WT.		CONC. PPM WT.
Uranium	2	Gadolinium	1	Chlorine	250
Thorium	5	Europium	0.6	Yttrium	37
Bismuth	2	Samarium	2	Strontium	160
Lead	MC	Neodymium	5	Rubidium	39
Thallium	11	Praseodymium	2	Bromine	39
Mercury*	16	Cerium	58	Selenium	55
Gold		Lanthanum	47	Arsenic	630
Platinum		Barium	MC	Germanium	45
Indium		Cesium	2	Gallium	150
Osmium		Iodine	9	Zinc	MC
Rhenium		Tellurium	0.1	Copper	300
Tungsten	0.8	Antimony	35	Nickel	47
Tantalum	<0.1	Tin	41	Cobalt	3
Hafnium	0.4	Cadmium	***33	Manganese	>460
Lutetium	<0.1	Silver	5	Chromium	51
Ytterbium	0.5	Palladium		Vanadium	230
Thulium	<0.1	Rhodium		Scandium	1
Erbium	0.2	Ruthenium		Fluorine**	~160
Holmium	0.2	Molybdenum	13	Boron	19
Dysprosium	0.9	Niobium	9	Beryllium	2
Terbium	0.2	Zirconium	29	Lithium	16

All elements not reported <0.1 ppm weight

* Flameless Atomic Absorption

** Specific Ion Electrode

*** Heterogeneous

MC - Major Component i.e. > 1000 ppm

(a) Determinations by Commercial Testing and Engineering Co., Chicago, Illinois. Trace Elements obtained by Spark Source Mass Spectrometry.

TABLE 15. FIRETUBE FLY ASH CHEMICAL ANALYSTS -
TEST 3, ECO-FUEL II(a)

PROXIMATE ANALYSIS			ULTIMATE ANALYSIS		
	As Rec'd.	Dry Basis		As Rec'd	Dry Basis
%Moisture	1.72	xxxxx	%Moisture	1.72	xxxxx
%Ash	60.33	61.39	%Carbon	31.05	31.59
%Volatile	13.11	13.34	%Hydrogen	0.38	0.39
% Fixed Carbon	24.84	25.27	%Nitrogen	0.39	0.40
	100.00	100.00	%Chlorine	1.93	1.96
			%Sulfur	2.48	2.52
Btu/lb.	4590	4670	%Ash	60.33	61.39
%Sulfur	2.48	2.52	%Oxygen (diff)	1.72	1.75
				100.00	100.00

ELEMENT		TRACE ELEMENTS		ELEMENT	
	CONC. PPM WT.		CONC. PPM WT.		CONC. PPM WT.
Uranium	4	Gadolinium	1	Yttrium	12
Thorium	5	Europium	0.3	Strontium	72
Bismuth	15	Samarium	2	Rubidium	17
Lead	MC	Neodymium	5	Bromine	98
Thallium	12	Praseodymium	2	Selenium	55
Mercury*	54	Cerium	26	Arsenic	94
Gold	<0.1	Lanthanum	37	Germanium	10
Platinum		Barium	MC	Gallium	15
Indium		Cesium	2	Zinc	MC
Osmium		Iodine	5	Copper	150
Rhenium		Tellurium	0.3	Nickel	25
Tungsten	1	Antimony	160	Cobalt	3
Tantalum	<0.1	Tin	100	Manganese	>460
Hafnium	<0.4	Cadmium	73	Chromium	210
Lutetium		Silver	***5	Vanadium	34
Ytterbium		Palladium		Scandium	1
Thulium	<0.1	Rhodium		Fluorine**	~160
Erbium	0.4	Ruthenium		Boron	19
Holmium	0.5	Molybdenum	40	Beryllium	0.7
Dysprosium	0.9	Niobium	6	Lithium	42
Terbium	0.2	Zirconium	29		

All elements not reported <0.1 ppm weight

* Flameless Atomic Absorption

** Specific Ion Electrode

*** Heterogeneous

MC - Major Component i.e., > 1000 ppm

(a) Determinations by Commercial Testing and Engineering Co., Chicago, Illinois. Trace Elements obtained by Spark Source Mass Spectrometry.

The residues collected contained between 30-50 percent carbon, and had a fairly high heating value (4500-7000 Btu/lb). Although much of the residue was inorganic, no mineral analyses were performed on the samples. However, the trace metals analyses of the samples found the following:

- Increasing levels of Pb, Zn, Sb, Sn, Hg, and Cr in the residue as the relative proportion of RDF increased (and coal decreased) in the fuel.
- Decreasing quantities of As, Cu, Zr, Ga, Ni, and V in the residue as the relative proportion of RDF increased (and coal decreased) in the fuel.

Many of the other metals that were detected were at very low concentrations, and did not show any trend of increasing or decreasing as the composition of the fuel changed by addition of RDF.

Grate Ash Composition

Only on one experiment (Test 2) was a detailed analysis performed on the composition and characteristics of the ash taken from the grate of the boiler. This information is presented in Tables 16 and 17.

An earlier study conducted by Battelle on a stoker boiler firing a mixture of coals and shredded refuse found some similarities in the analysis of the grate ash⁽¹²⁾. The concentrations of barium, strontium, zinc, and nickel found in the grate ash from that study were approximately equal to the values reported in this study. However, this study found large concentrations (>500 ppm) of copper, manganese and chromium in the grate ash, while quantities less than 300 ppm were reported in the previous study (see Table 18.).

The detailed mineral analysis of the grate ash from Test 2 also showed a large concentration of sulfur trioxide (2.69 percent). The form of the sulfur in the bed ash was probably a sulfate rather than sulfur trioxide. An increase in the sulfur content of the grate ash was also reported in the other Battelle study⁽¹²⁾. In that study it was found that as RDF was added to the coal feed, the concentration of sulfur in the grate ash increased from <1 percent to as high as 4.9 percent when 38 wt percent refuse was added to high sulfur (2.4 percent) coal.

TABLE 16. BOTTOM ASH CHEMICAL ANALYSIS -
TEST 2, COAL + ECO-FUEL II^(a)

<u>MINERAL ANALYSIS OF ASH</u>	<u>Percent Weight Ignited Basis</u>
Silica, SiO_2	55.16
Alumina, Al_2O_3	18.61
Titania, TiO_2	1.49
Ferric oxide, Fe_2O_3	8.68
Lime, CaO	5.93
Magnesia, MgO	1.37
Potassium oxide, K_2O	1.71
Sodium oxide, Na_2O	3.54
Sulfur trioxide, SO_3	2.69
Phos. pentoxide, P_2O_5	0.50
Strontium Oxide, SrO	0.01
Barium Oxide, BaO	0.09
Manganese Oxide, Mn_3O_4	0.22
Undetermined	0.00
	<u>100.00</u>

	<u>FUSION TEMPERATURE OF ASH</u>	
	<u>Reducing</u>	<u>Oxidizing</u>
Initial Def., IT	2090°F	2190°F
Softening, ST	2270°F	2360°F
Softening, HT	2320°F	2410°F
Fluid, FT	2550°F	2640°F

(a) Determinations by Commercial Testing and Engineering Co.,
Chicago, Illinois

TABLE 17. BOTTOM ASH CHEMICAL ANALYSIS
TEST 2, COAL + ECO-FUEL II (a)

		TRACE ELEMENTS			
ELEMENT	CONC. PPM WT.	ELEMENT	CONC. PPM WT.	ELEMENT	CONC. PPM WT.
Uranium	13	Gadolinium	4	Chlorine	6
Thorium	39	Europium	2	Yttrium	75
Bismuth		Samarium	8	Strontium	580
Lead	74	Neodymium	25	Rubidium	79
Thallium	<0.5	Praseodymium	12	Bromine	3
Mercury*	0.03	Cerium	110	Selenium	<4
Gold		Lanthanum	94	Arsenic	42
Platinum		Barium	MC	Germanium	8
Indium		Cesium	5	Gallium	67
Osmium		Iodine	0.4	Zinc	480
Rhenium		Tellurium	0.3	Copper	MC
Tungsten	5	Antimony	71	Nickel	380
Tantalum	0.3	Tin	8	Cobalt	31
Hafnium	2	Cadmium	2	Manganese	>920
Lutetium	0.2	Silver	<0.8	Chromium	MC
Ytterbium	2	Palladium		Vanadium	68
Thulium	0.3	Rhodium		Scandium	12
Erbium	2	Ruthenium		Fluorine**	~ 7
Holmium	3	Molybdenum	25	Boron	85
Dysprosium	4	Niobium	47	Beryllium	3
Terbium	1	Zirconium	230	Lithium	6

All elements not reported <0.1 ppm weight

* Flameless Atomic Absorption

** Specific Ion Electrode

MC - Major Component i.e., > 1000 ppm

(a) Determinations by Commercial Testing and Engineering Co.,
Chicago, Illinois

TABLE 18. CHEMICAL ANALYSIS OF BOTTOM ASH
FROM OTHER STOKER FIRED BOILER
Data from Reference 12

	Composition of Grate Ash (PPM)				
	High Sulfur Coal (5.2% S)	High Sulfur Coal (3.3% S)	27 wt % Refuse + High Sulfur Coal (5.2%)	38 wt % Refuse and High Sulfur Coal (2.4% S)	52 wt % Refuse + High Sulfur Coal (2.4% S)
Pb	200	100	30	100	100
As	<1000	<1000	<1000	<1000	<1000
Zn	<1000	<1000	<1000	<1000	<1000
Mn	100	300	100	200	300
Cr	50	100	50	<100	100
Cu	300	30	100	100	200
Sr	300	300	600	200	300
Composition of Particulates (PPM)					
Pb	300	3000	3000	300	800
As	<1000	1000	<1000	<1000	<1000
Zn	500	3000	3000	<1000	1000
Mn	50	200	300	300	500
Cr	100	100	200	<100	600
Cu	100	1000	200	100	300
Sr	300	100	300	200	300

Hydrocarbon Emissions

Continuous analysis for total hydrocarbons was accomplished with a flame ionization detector (FID). In all of the experiments, the total hydrocarbon average levels were observed to be less than 20 ppm. Since the emission levels were very nearly at the lowest detection levels of the FID, it is probably that the true hydrocarbon emission levels were somewhat lower.

Grab samples of the flue gas were collected and immediately analyzed by gas chromatography for hydrocarbons several times during each test run. With the exception of Test 2, no hydrocarbons above C-1 were detected at all, and most specimens contained less than 1 ppm of hydrocarbon measured as methane. This indicates that burning was very complete as provided by the good mixing (over fire jets) and adequate excess air. Tables 19 thru 24 show these analyses as obtained using level one techniques.

Boiler tests in England⁽⁵⁾ using densified RDF (pellets) resulted in gaseous organic emissions only slightly higher than those obtained in this program. The English tests resulted in total hydrocarbon emissions (as C₃) of 15 and 11 ppm THC for 50% and 100% pelletized RDF burning respectively, whereas this program only observed hydrocarbons with boiling points above -100 C in one test, and all organic emissions were below 5 ppm as measured by gas chromatography.

CHEMICAL ANALYSIS OF SASS SPECIMENS

The gaseous and particulate samples that were extracted from each test were analyzed according to Level One procedures. The samples that were collected by the SASS train were categorized as follows:

- Particulate 10 μ m in diameter and greater
- Particulates 3 μ m in diameter and greater, but less than 10 μ m
- Particulates 1 μ m in diameter and greater, but less than 3 μ m
- Particulates less than 1 μ m
- Gaseous samples collected by YAD-2 column and solution impingers.

TABLE 19. HYDROCARBON ANALYSIS OF FLUE GAS BY
GAS CHROMATOGRAPHY - Test 1, Coal

Level 1 Designation	bp Range (C)	Sampling Time, EST →	Hydrocarbon Concentration, mg/m ³				
			1258	1323	1405	1457	1610(a) 1622
GC1	-160 to -100		1.5	0.7	0.9	1.9	0.8 0.6
GC2	-100 to -50		ND(b)				
GC3	-50 to 0		ND(b)				
GC4	0 to 30		ND(b)				
GC5	30 to 60		ND(c)				
GC6	60 to 90		ND(c)				
GC7	90 to 100		ND(c)				

(a) Sample taken from heated Teflon line in control room. All other samples taken directly from stack at port adjacent to SASS train

ND(b) - None detected (<0.1 mg/m³) in any of the samples

ND(c) - None detected (<0.05 mg/m³) in any of the samples.

TABLE 20. HYDROCARBON ANALYSIS OF FLUE GAS BY GAS
CHROMATOGRAPHY
Test 2, Eco-Fuel II + Coal

Level 1 Designation	bp Range, C	Sampling Time, hrs EST→	Hydrocarbon Concentration in Flue Gas, mg/m ³						
			1012(a)	1111(a)	1155	1213(c)	1224	1401(a)	1439
GC 1	-160 to -100		0.6	0.8	0.6	0.8	0.9	0.7	0.7
GC 2	-100 to -50		ND ^(b)						
GC 3	-50 to 0		ND						
GC 4	0 - 30		ND						
GC 5	30 to 60		0.7	0.4	0.4		0.3	0.5	0.4
GC 6	60 to 90		ND						
GC 7	90 to 100		ND						

(a) Grab sample from stack, remainder of samples from heated instrument sample line.

(b) ND - none detected (<0.03 mg/m³) in any of the samples.

(c) Not analyzed for C₅-C₇ hydrocarbons.

TABLE 21. HYDROCARBON ANALYSIS OF FLUE GAS BY GAS
CHROMATOGRAPHY
Test 3, Eco-Fuel II

Level 1 Designation	bp Range, C	Sampling Time, Hrs EST—▶	Hydrocarbon Concentration in Flue Gas, mg/m ³						
			1013(a)	1121	1133	1337	1349	1604	1618
GC 1	-160 to -100		1.0	0.4	0.4	1.8	0.8	1.2	1.3
GC 2	-100 to -50		ND ^(b)						▶
GC 3	-50 to 0		ND						▶
GC 4	0 to 30		ND						▶
GC 5	30 to 60		ND						▶
GC 6	60 to 90		ND						▶
GC 7	90 to 100		ND						▶

(a) Grab sample from stack, all other samples taken from heated instrument sample line.

(b) ND - not detected (<0.03 mg/m³) in any of the samples.

TABLE 22. HYDROCARBON ANALYSIS OF FLUE GAS
BY GAS CHROMATOGRAPHY
Test 4, Americology + Coal

Level 1 Designation	bp Range, C	Sampling Time—▶	Hydrocarbon Concentration in Flue Gas, mg/m ³						
			1022(a)	1148	1156	1217	1425(a)	1448(a)	1547(a) 1655(a)
GC 1	-160 to -100		0.9	1.8	1.9	2.6	1.5	2.3	0.9 1.4
GC 2	-100 to -50		ND ^(b)						▶
GC 3	-50 to 0		ND						▶
GC 4	0 to 30		ND						▶
GC 5	30 to 60		ND						▶
GC 6	60 to 90		ND						▶
GC 7	90 to 100		ND						▶

(a) Grab sample from stack, remainder of samples from heated instrument sample line.

(b) ND - not detected (<0.03 mg/m³) in any of the samples.

TABLE 23. HYDROCARBON ANALYSIS OF FLUE GAS
BY GAS CHROMATOGRAPHY
Test 5, Americology

Level 1 Designation	bp Range, C	Sampling Time, Hrs EST	Hydrocarbon Concentration in Flue Gas, mg/m ³ (a) (b)									
			1124	1218	1306	1355	1412	1437	1527	1558	1610	
GC 1	-160 to -100		1.1 - 1.2 ^(c)	1.1 - 1.2 ^(c)	0.7	0.6	0.5	0.6	0.5	0.6	0.7	
GC 2	-100 to -50		ND(b)									
GC 3	-50 to 0		ND									
GC 4	0 to 30		ND									
GC 5	30 to 60		ND									
GC 6	60 to 90		ND									
GC 7	90 to 100		ND									

(a) All samples taken from stack.

(b) ND - not detected (<0.03 mg/m³) in any of the samples.

(c) Duplicate analyses.

TABLE 24. HYDROCARBON ANALYSIS OF FLUE
GAS BY GAS CHROMATOGRAPHY
Test 6, Eco-Fuel II + Coal + Hazardous Waste

Level I Designation	bp Range, C	Sampling Time, Hrs EST	Hydrocarbon Concentration in Flue Gas, mg/m ³ (a)(b)									
			0936	1004	1025	1106	1150	1236	1314	1416	1442	1530
GC 1	-160 to -100		0.9	0.7	0.8	0.8	0.6	0.5	0.5	0.9	0.5	1.2
GC 2	-100 to -50		ND(b)									
GC 3	-50 to 0		ND									
GC 4	0 to 30		ND									
GC 5	30 to 60		ND									
GC 6	60 to 90		ND									
GC 7	90 to 100		ND									

(a) All samples taken from stack.

(b) ND - not detected, ($<0.03 \text{ mg/m}^3$) in any of the samples.

The two smaller sizes of particulates, i.e., smaller than 3 μm , are referred to as the respirable particulates. These received more attention because of their high lung retention characteristics.

Not all of the samples collected were subjected to the same chemical analyses. Table 25 indicates the samples that were selected for analysis and the type of analysis that was performed.

Toxic Metals

The concentrations of 6 toxic metals in the flue gases and respirable suspended particulates are shown on Table 26. Because of the relatively high volatility of mercury, more was generally found in the vapor state than in (or on) the suspended particulates. Battelle's experience with similar emissions indicates that most of the gaseous mercury is retained in the XAD-2.

High levels of lead were found in the particulate samples taken from the two tests in which refuse was the only fuel (tests 3 and 5). The lead concentrations from the RDF tests were an order of magnitude above that found in the particulate samples collected during the test where coal was the only fuel. The lead concentrations in particulates correspond to stack emissions as follows:

- Coal only - 15.9 $\mu\text{g}/\text{M}^3$
- Eco-Fuel II only - 7,020 $\mu\text{g}/\text{M}^3$
- Americology only - 19,300 $\mu\text{g}/\text{M}^3$

These high concentrations of lead when burning RDF are consistent with the high lead content in the fuel as shown on Table 4. A larger portion of the lead in the Americology resulted in gaseous emissions than from the Eco-Fuel or from the coal.

Trace Metals

The respirable particulates were also analysed for trace metals by spark source mass spectrometry (SSMS), and these results are shown on Table 21. A SSMS technique was used to identify trace metals constituents in certain SASS samples. The 1 μg cyclone and the particulate filter samples from the first five tests were submitted for SSMS analysis, with the results listed on Table 27.

TABLE 25. SASS SAMPLES ANALYZED

Analyses	Test Number																				
	1			2			3			4			5			6			7		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
POM																					
Trace Metals	X			X																	
Hg	X	X					X	X													
Toxic Metals	X																				
TCO/GRAY	X	X		X			X	X		X	X										
Organic, by I.R.	X	X		X			X	X		X	X										
LC followed by I.R.																					
Inorganics	X	X		X			X	X													
Radionuclides	X	X					X	X													
Dioxins							X	X													

(a): Particulates 3 μm and larger

(b): Particulates smaller than 3 μm

(c): Gas Sample

(a): Particulates 3 μ m and larger
 (b): Particulates smaller than 3 μ m
 (c): Gas Sample

TABLE 26. TOXIC METALS ANALYSES

Test Number	SASS Sample	Expressed in $\mu\text{g/g}$ Of Particulate ($\mu\text{g}/\text{M}^3$ Plume Gas) (a)							
		Hg	As	Sb	Pb	Te	Re		
1	<1 μm , i.e., filter catch	0.33 (.0148)	1030 (46.0)	275 (12.3)	3560 (159)	1.0 (.1)	13.0 (.581)		
1	XAD-2 column	(7.04)	-	-	-	-	-		
2	XAD-2 column	(1.15)	-	-	-	-	-		
3	<1 μm , i.e., filter catch	0.20 (0.0183)	250 (22.8)	940 (85.9)	76,800 (7,020)	<1.0 <0.1	<2.0 (.2)		
3	XAD-2 column	(0.52)	-	-	-	-	-		
5	<1 μm , i.e., filter catch	0.20 (.0752)	120 (45.1)	542 (204)	51,200 (19,300)	<1.0 (.4)	<2.0 (.8)		
5	XAD-2 column	(6.18)	-	-	-	-	-		
6	MATE values (b)	(50)	(2)	(500)	(150)	(100)	(2)		

(a) Corrected to 20C, 1 ATM, 12% CO₂, Dry

(b) Minimum Acute Toxicity Effluent. This is an indication of the maximum allowable concentration that should be emitted for environmental reasons.

TABLE 27. TRACE METALS ANALYSIS OF
RESPIRABLE PARTICULATES

Element	Test Number ^(a)				
	1	2	3	4	5
Uranium	< 5.57E-1	< 1.00E-1	< 3.63E-1	< 2.00E-2	< 4.43E-1
Thorium	< 1.11E+0	< 1.00E-1	< 3.63E-1	< 5.00E-1	< 4.43E-1
Bismuth	5.57E+0	3.00+0	1.21E+1	8.00+0	1.48E+1
Lead	1.11E+3	6.00+3	3.63E+4	3.00E+4	8.87E+4
Thallium	4.45E+1	3.00+0	7.27E-1	< 2.00E+1	8.87E+0
Mercury	< 2.23E+1	< 5.00E-1	< 3.63E+0	2.00+0	< 4.43E+0
Gold	< 5.57E-1	< 1.00E-2	< 1.21E-1	< 7.00E-2	< 1.48E-1
Platinum	< 1.11E+0	< 4.00E-2	< 3.63E-1	< 2.00E-2	< 4.43E-1
Iridium	< 1.11E+0	< 4.00E-2	< 3.63E-1	< 2.00E-2	< 4.43E-1
Osmium	< 2.23E+0	< 4.00E-2	< 3.63E-1	< 2.00E-2	< 4.43E-1
Rhenium	< 1.11E+0	< 4.00E-2	< 2.42E-1	< 2.00E-2	< 4.43E-1
Tungsten	< 1.11E+0	< 5.00E-1	< 3.63E-1	< 2.00E-1	< 4.43E-1
Tantalum	< 3.34E+0	< 3.00E-1	< 4.84E+0	< 1.00+0	< 5.91E+0
Hafnium	< 1.11E+0	< 3.00E-1	< 1.82E+0	< 1.00+0	< 2.22E+0
Lutecium	< 5.57E-1	< 2.00E-2	< 1.21E-1	< 7.00E-2	< 1.48E-1
Ytterbium	< 1.11E+0	< 5.00E-2	< 3.63E-1	< 4.00E-1	< 4.43E-1
Thulium	< 5.57E-1	< 2.00E-2	< 1.21E-1	< 7.00E-2	< 1.48E-1
Erbium	< 1.11E+0	< 4.00E-2	< 2.42E-1	< 1.00E-1	< 2.96E-1
Holmium	< 5.57E-1	< 2.00E-2	< 1.21E-1	< 1.00E-1	< 1.48E-1
Dysprosium	< 1.11E+0	< 5.00E-2	< 3.63E-1	< 2.00E-2	< 4.43E-1
Terbium	< 3.34E-1	< 2.00E-2	< 1.21E-1	< 1.00E-1	< 2.96E-1
Gadolinium	< 1.11E+0	< 5.00E-2	< 3.63E-1	< 2.00E-2	< 4.43E-1
Europium	< 1.11E+0	< 4.00E-2	< 2.42E-1	< 1.00E-1	< 2.96E-1
Samarium	< 1.11E+0	< 9.00E-2	< 3.63E-1	< 4.00E-1	< 7.39E-1
Neodymium	< 3.34E+0	< 9.00E-2	< 6.06E-1	< 4.00E-1	< 1.48E+0
Praseodymium	< 3.34E-1	2.00E-2	< 1.21E-1	< 2.00E-1	< 2.96E-1
Cerium	< 1.67E-1	< 2.00E-2	< 1.21E-1	< 4.00E-1	< 1.48E+0
Lanthanum	< 3.34E-1	2.00E-2	< 6.06E-2	< 7.00E-2	< 1.48E-1

TABLE 27. (Continued)

Element	Test Number (a)				
	1	2	3	4	5
Barium	5.57E+0	2.25E0	8.48E+0	5.00E-2	3.10E+1
Cesium	8.35E-2	4.00E-2	1.21E+0	2.00E-1	7.39E+0
Iodine	< 5.01E-1	< 3.00E-2	< 9.08E-2	< 3.00E-1	< 1.11E-1
Tellurium	< 1.11E+0	< 4.00E-2	< 3.63E-1	< 2.00E-1	< 4.43E-1
Antimony	2.00E+1	5.00E+1	7.27E+1	4.00E+2	8.87E+1
Tin	1.11E+2	3.00E+2	6.06E+2	2.00E+2	7.39E+2
Indium	1.11E+0	9.00E-1	2.42E+0	< 4.00E+0	< 2.96E+0
Cadmium	1.00E+2	1.00E+2	3.63E+2	4.00E+2	8.87E+2
Silver	1.67E+0	2.00E+1	1.21E+1	2.00E+2	2.43E+2
Palladium	< 1.11E+0	< 5.00E-2	< 2.42E-1	< 2.00E-1	< 2.96E-1
Rhodium	< 3.34E+0	< 5.00E-2	< 3.63E+0	< 2.00E+0	< 4.43E+0
Ruthenium	< 1.11E+0	< 8.00E-2	< 6.06E-1	< 7.00E-1	< 7.39E-1
Molybdenum	1.67E+1	< 2.00E+1	1.21E+1	< 7.00E+1	1.48E+1
Niobium	< 3.34E+0	< 8.00E+0	< 3.63E+0	< 4.00E-1	< 4.43E+0
Zirconium	< 1.11E+0	< 5.00E-1	< 7.27E-1	< 5.00E+0	< 2.22E+0
Yttrium	< 2.23E-1	< 8.00E-2	< 1.21E-1	< 4.00E-1	< 4.43E-1
Strontium	4.45E-1	< 8.00E-2	1.82E-1	< 7.00E-1	7.39E-1
Rubidium	1.11E+1	< 2.00E+1	3.03E+1	1.00E+2	2.22E+2
Bromine	< 8.35E-1	4.00E+1	< 4.84E-1	2.00E+3	< 2.96E+0
Selenium	< 7.79E-1	4.00E+0	< 2.42E-1	3.00E+1	< 2.96E-1
Arsenic	1.67E+2	8.00E+1	3.63E+1	4.00E+2	4.43E+1
Germanium	< 2.23E+0	8.00E+1	< 1.21E+0	4.00E+2	< 1.48E-1
Gallium	2.78E+2	3.00E+1	3.63E+0	1.00E+2	8.87E+0
Zinc	3.33E+3	1.00E+4	2.42E+4	4.00E+4	2.95E+4
Copper	1.50E+2	5.00E+1	3.47E+2	7.00E+2	2.79E+2
Nickel	1.11E+2	2.00E+1	< 2.42E+0	7.00E+1	< 2.96E+0
Cobalt	1.67E+2	4.00E+0	< 1.21E+0	2.00E+1	< 1.48E+0
Iron	1.64E+3	2.00E+2	2.63E+1	1.00E+3	1.13E+2

TABLE 27. (Continued)

Element	Test Number (a)				
	1	2	3	4	5
Manganese	3.35E+0	5.00E0	8.65E+0	7.00E+1	7.04E+1
Chromium	6.61E+0	2.00E+1	1.20E+1	1.00E+2	4.43E+1
Vanadium	6.68E+0	5.00E0	1.21E+0	1.00E+2	2.96E+0
Titanium	1.67E+1	1.00E+1	< 2.42E-1	3.00E+1	3.87E+0
Scandium	< 3.34E-1	< 4.00E-2	< 2.54E-1	< 2.00E-1	< 3.10E-1
Calcium	1.39E+2	1.00E+1	NG	2.00E+2	1.79E+2
Potassium	8.91E+1	1.00E+4	1.79E+3	5.00E+4	8.86E+4
Chlorine	2.00E+2	2.00E+2	5.85E+2	2.00E+4	3.67E+3
Sulphur	1.11E+2	3.00E+2	6.06E+2	4.00E+4	1.48E+3
Phosphorus	1.32E+2	9.00E+1	1.20E+2	7.00E+2	1.46E+2
Silicon	1.34E+2	6.00E+2	2.57E+1	5.00E+2	3.51E+1
Aluminum	6.35E+1	2.00E+1	NG	6.00E+1	NG
Magnesium	2.23E+1	1.00E+1	3.03E+1	2.00E+0	1.48E+1
Sodium	2.67E+2	2.00E+4	1.08E+4	7.00E+4	1.32E+4
Fluorine	< 2.23E+0	1.00E+0	< 7.27E-1	4.00E+0	< 8.87E-1
Boron	6.69E-1	2.00E+0	NG	6.00E+0	9.35E-2
Beryllium	1.11E+0	< 4.00E-4	6.06E-3	1.00E-1	< 3.69E-3
Lithium	6.65E+0	5.00E-1	6.93E-1	2.00E+0	4.10E-1

(a) Note: All values are reported in micrograms/M³, and corrected for blank values and solvent impurities.

NG - No good due to high blank value

A few trends are evident from the SSMS data on Table 27. The potassium and zinc concentrations were higher in the tests burning RDF while nickel and iron concentrations were lower. Part of the difficulty that is associated with interpreting this data is the poor resolution that is inherent in SSMS analyses. The uncertainty for any values reported on Table 27 may be ± 100 percent. With such a large error, small changes in concentrations are easily masked and detailed interpretation of the data is difficult.

TCO/GRAV Analysis

A total chromatographable organic (TCO) analysis and a gravimetric (GRAV) analysis were performed on 9 samples extracted from 5 tests. The samples analyzed were:

- Run No. 1 - respirable particulates and XAD-2 column
- Run No. 2 - XAD-2 column
- Run No. 3 - respirable particulates and XAD-2 column
- Run No. 4 - respirable particulates and XAD-2 column
- Run No. 5 - respirable particulates and XAD-2 column

The results of the TCO/GRAV analysis and the IR analysis of the samples are presented in Tables 28 and 29. Of these organic emissions, the respirable particulate contribution was insignificant compared to the organics collected from the gas stream. The organics collected when burning only RDF were appreciably higher than when burning coal only: over 7 times as high when burning Eco-Fuel II and over 20 times as high when burning the Americology. The cofiring tests resulted in intermediate emission rates for each RDF, as might be expected.

The IR analyses of the organics did not appear very different from one another, except that the analysis of the XAD-2 column in the Americology test found traces of amides that were not reported in any other analyses.

Only the extracts from Test 5 XAD-2 column yielded enough material for an LC analysis. This analysis is reported in Table 30.

TABLE 28. ORGANIC MATERIALS EXTRACTED FROM FLUE GAS AND RESPIRABLE PARTICULATES

Test Number	SASS Sample	Total Chromatographable Organics		Determination by Gravimetric Analyses		
		TCO mg/sample	$\mu\text{g}/\text{M}^3$ (a)	mg/sample	$\mu\text{g}/\text{M}^3$ (a)	Sum (TCO + GRAV) mg/sample $\mu\text{g}/\text{M}^3$ (a)
1	Respirable Particulates	ND	ND	0.71 (c)	(c)	(c)
1	XAD-2 column	0.2/0.02	(c)	3.2	130	3.2
2	Respirable Particulates	ND	ND	ND	ND	ND
2	XAD-2 column	12.4	510	1.8	66	14.2
3	Respirable Particulates	ND	ND	(c)	(c)	(c)
3	XAD-2 column	19.5	890	1.6	75	21.1
4	Respirable Particulates	ND	ND	(c)	(c)	(c)
4	XAD-2 column	23.6	1030	3.1	140	26.7
5	Respirable Particulates	-	-	1.4	59	1.4
5	XAD-2 column	27.6	1220	37.3	1650	64.9
-	XAD-2 Blank (b)	0.03	-	0.60	-	0.63
-	Filter Blank (b)	ND	-	0.72	-	0.72

(a) $\mu\text{g}/\text{M}^3$, 20C, 1ATM, 12% CO₂, dry

(b) These blank numbers have been subtracted from the directly measured weights to obtain the weights reported in this table.

(c) Blank weight exceeded the observed sample weight.

ND Not Determined

TABLE 29. ORGANIC CHARACTERIZATION OF TOTAL SAMPLE

Test Number	SASS Sample Location	Infrared Characterization
1	Respirable Particulates	Aliphatic hydrocarbon with some of at least two carbonyl containing compounds.
1	XAD-2 Column	Aliphatic acid and aromatic ester. A high frequency carbonyl is probably anhydride. A shoulder at 1660 cm^{-1} is unaccounted for.
2	XAD-2 Column	Acid and aromatics.
3	Respirable Particulates	Aliphatic hydrocarbon with some acid and ester. Large concentration of inorganic sulfate.
3	XAD-2 Column	Predominately saturated aliphatic acid. A second carbonyl is probably aromatic ester.
4	Respirable Particulates	Same as results from 3.
4	XAD-2 Column	Saturated aliphatic acid. There are two other carbonyl containing compounds which are probably aromatic ester and anhydride.
5	Respirable Particulates	Aliphatic hydrocarbon with a small amount of aliphatic ester.
5	XAD-2 Column	Acid and amide.
	XAD-2 Blank	Trace of hydrocarbon.
	Filter Blank	Aliphatic hydrocarbon with low levels of at least two carbonyl containing compounds.

TABLE 30. ORGANIC CHARACTERIZATION OF LIQUID
CHROMATOGRAPHY FRACTIONS
Test Run 5 Americology Fuel

XAD-2 Column extracts	Infrared Results
1	Aliphatic hydrocarbon
2	Aliphatic hydrocarbon, high in methyl, some ester, some C=C
3	Aliphatic and aromatic hydrocarbon, some ester
4	Amide, aromatic anhydride
5	Aromatic anhydride
6	Aromatic acid
7	Aromatic and aliphatic acid, acid salt
<u>Blank</u>	
1	Trace amount of aliphatic hydrocarbon
2	Trace amounts of aliphatic hydrocarbon and carbonyl
3	Trace amounts of aliphatic hydrocarbon and carbonyl
4	Trace amounts of aliphatic hydrocarbon and silicate
5	Trace amounts of ester, silicate, aromatics and acid salt
6	Small amounts of aromatic esters and acid and acid salt, but above background levels
7	Trace amounts of aliphatic hydrocarbon and ester

Polycyclic Organic Materials

The SASS specimens were analysed for traces of polycyclic organic materials (POM). The results are shown in Table 31 in concentrations per standard cubic meter of the gas when corrected to 12% CO₂.

Several observations from these limited tests can be noted:

- The POM emissions from burning only Americology exceed those from burning only Eco-Fuel II
- The largest quantities of POM were collected from the gas phase
- The high molecular weight species (which have greater health significance) were detected only when burning only RDF
- These heavier species were detected only in the gas phase, presumably related to the temperature in the SASS oven.

Even these low concentrations of the heavy species are significant. For example the benzo-a-pyrene gaseous emission was observed to be above 0.2 µg/M³ whereas the goal for emission of this specie is only 0.02 µg/M³ according to the MATE objectives of EPA.

Dioxin Analysis

Four samples were submitted for an analysis to determine the presence, if any, of 2,3,7,8 Tetrachlorodibenzo-p-dioxin (TCDD). The samples that were submitted were:

- Test 3 - 1 µm cyclone/filter and XAD-2 column
- Test 5 - 1 µm cyclone/filter and XAD-2 column

These samples were submitted because they were tests in which RDF was the only fuel and it was anticipated that if any dioxins were present that they would be found in these tests. The results of the analyses are shown in Table 32. Although detectable quantities of dioxin appear to be present in the XAD-2 column from Test 5 (see last line in Table 32), it is the opinion of the analytical staff that high levels of background noise are responsible for the detected quantities of TCDD. It is concluded, therefore, that no TCDD was found in any of the samples submitted. Thus, it appears that refuse combustion under these laboratory conditions does not produce this dioxin in either a gaseous or particulate form.

TABLE 31. POM EMISSIONS
 $\mu\text{g}/\text{M}^3(\text{c})$
 As determined by GC/MS

Species	Flue Gas(a)			Sub Micron Particulate(b)	
	<u>3</u>	<u>4</u>	<u>5</u>	<u>3</u>	<u>5</u>
Naphthalene	9.17	10.9	44.7	0.26	0.28
Acenaphthene	0.43	1.95	05.08	< 0.06	< 0.06
Acenaphthylene	0.19	0.40	0.88	< 0.06	< 0.20
Fluorene	0.37	.62	0.66	< 0.06	< 0.06
Phenanthrene	0.80	4.20	4.91	< 0.06	< 0.06
Anthracene	0.36	3.97	3.36	< 0.06	< 0.06
Methylanthracene	< 0.06	< 0.06	0.28	< 0.06	< 0.06
Fluoranthene	0.45	2.57	3.14	< 0.06	< 0.06
Pyrene	0.25	.48	1.99	< 0.06	< 0.06
Methylpyrene	< 0.06	< 0.06	0.22	< 0.06	< 0.06
Benzo(a)anthracene	0.63	.62	0.61	< 0.06	< 0.06
Chrysene	0.40	< 0.06	0.41	< 0.06	< 0.06
Methylchrysene	< 0.06	< 0.06	< 0.06	< 0.06	< 0.06
Dimethylbenzo(a)anthracene	< 0.06	< 0.06	< 0.06	< 0.06	< 0.06
Benzo(a)fluoranthene	0.41	< 0.06	0.43	< 0.06	< 0.06
Benzo(e)pyrene	0.28	< 0.06	0.25	< 0.06	< 0.06
Benzo(a)pyrene	0.28	< 0.06	0.24	< 0.06	< 0.06
Perylene	0.34	< 0.06	0.33	< 0.06	< 0.06
Indeno(1,2,3-cd)pyrene	0.53	< 0.06	0.51	< 0.06	< 0.06
Benzo(g,h,i)perylene	0.36	< 0.06	0.34	< 0.06	< 0.06
Coronene	0.44	< 0.06	0.06	< 0.06	< 0.06
Dibenzopyrene	< 0.06	< 0.06	< 0.06	< 0.06	< 0.06
Total(d)	15.7	25.7	68.3	0.26	0.48

- (a) XAD-2 Column extracts
 (b) Filter catch extracts
 (c) $\mu\text{g}/\text{M}^3$ @ 1ATM, 20C and 12% CO_2 (dry)
 (d) Zero values were assumed for the values which were below the detection limits.

TABLE 32. DIOXIN ANALYSES

	SASS Sample Location	Sample Weight (g)	A $\frac{m/e\ 320}{m/e\ 322}$	Total 2,3,7,8-TCDD (pg)	Limit of Detection (PPT)
3	1 μ m cyclone/ filter	0.5	-	ND	300
3	XAD-2 Column	15.2	-	ND	5
5	1 μ m cyclone/ filter	1.7	-	ND	50
5	XAD-2 Column	14.9	1.17	590	11

Note: A-Ratio should be 0.77. Usually a range of 0.68 - 0.85 is acceptable.

Run 3 - ECO-FUEL II only

Run 5 - Americology only

ND - Not detected

Radionuclides Analysis

A radionuclides scan was made on six extracts of combined samples of suspended particulates taken from the SASS train. The samples that were analyzed were:

- Test 1 - 10 μm /3 m cyclones and 1 μm cyclone/filter
- Test 3 - 10 μm /3 m cyclones and 1 μm cyclone/filter
- Test 5 - 10 μm /3 m cyclones and 1 μm cyclone/filter

Each sample was scanned for the following isotopes:

- ^{14}C
- ^3H
- ^{125}I
- ^{137}Cs
- ^{51}Cr
- ^{57}Co

Both the soft β emissions from the carbon and hydrogen and the hard γ from the metals were within background levels indicating no significant radiations from any of the specimens.

SECTION 9

DATA REPRODUCIBILITY

Although no tests were duplicated during this program 3 tests (Test 2, 6, and 7) were similar enough in fuel composition and operating conditions to warrant a statistical evaluation of the experimental results. An analysis was performed on the particulate and SO₂ measurements, since these are the two emission measured which should not have changed in the 3 tests.

Particulates

The particulates measured for the three tests were:

- Test 2: 167 mg/M³ @ 12 percent CO₂, 20C and 1 ATM
- Test 6: 186 mg/M³ @ 12 percent CO₂, 20C and 1 ATM
- Test 7: 206 mg/M³ @ 12 percent CO₂, 20C and 1 ATM

The average particulate emissions value for the 3 tests is 186 ± 19.5 mg/M³. This indicates an experimental uncertainty of ± 10.5 percent.

Sulfur Dioxide

The SO₂ measurements for the 3 tests were:

- Test 2: 589 ppm @ 12 percent CO₂
- Test 6: 543 ppm @ 12 percent CO₂
- Test 7: 480 ppm @ 12 percent CO₂

The average SO₂ emissions value for the 3 test is 537 ± 54.7 ppm, which is equivalent to an experimental uncertainty of 10.2 percent, matching the uncertainty of the particulates analyses.

Based upon these two analyses the overall experimental uncertainty for the 3 tests is approximately 10 percent. The best estimate that can be made as to the experimental uncertainty of the entire program is that it is also approximately 10 percent.

SECTION 10

APPLICATIONS OF THESE TEST RESULTS

The principal value of the results of the tests reported herein lies in their comparison with the two related programs using laboratory scale systems (see Section 4). This comparison should demonstrate the effects of type of RDF burning on stack emissions more accurately than a direct comparison of these laboratory scale data with full scale RDF co-firing data. The temperatures, mixing, fuel compositions and fuel preparations and firing obtained in these small laboratory scale systems can be more directly related to larger systems than the residence times involved. The residence time in full scale industrial RDF burning is much longer, especially in the gas phase reactions that occur above a bed in a stoker-fired boiler.

Further analysis of the data presented in this report can be performed once the results from the related programs are available.

REFERENCES

1. IERL-RTP Procedures Manual: Level 1 Environmental Assessment Second Edition, EPA-600/7-78-201, October, 1978
2. Hollander, H. I., Parametric Considerations in Utilizing Refuse Derived Fuels in Existing Boiler Furnaces. In: Proceedings of the 1976 National Waste Processing Conference, ASME, Boston, Massachusetts, May 23-26, 1976.
3. Mrus, S. T., and Prendergast, C. A., Heating Value of a Refuse Derived Fuel. In: Proceedings of the 1978 National Waste Processing Conference, ASME, Chicago, Illinois, May 7-10, 1978.
4. Sarofim, A. F., Combustion Chemistry and Modeling: An Overview. Proceedings of the Stationary Source Combustion Symposium, Atlanta, Georgia, Sept., 1975.
5. Birch, P. R., and Jackson, D. V., as reported by Albert and Alter, "A Survey of U. S. and European Practice for Recovering Energy from Municipal Waste" in Progress in Biomass Conversion V. 1.
6. Degler, G. N. and Wiles, C. C., Co-Firing Densified Refuse Derived Fuel in a Spreader Stoker-Fired Boiler, Presented at EPA Conference on Waste-to-Energy Technology Update April, 1980.
7. Miller, P. D., Krause, H. H., Vaughan, D. A., and Boyd, W. K., The Mechanism in Temperature Corrosion in Municipal Incinerators. Corrosion, V. 28. 1972, 274 pp.
8. Miller, P. D., Krause, H. H., Zupan, J., and Boyd, W. K., Corrosive Effects of Various Salt Mixtures Under Combustion Gas Atmospheres. Corrosion, V. 2. 1972, 222 pp.
9. Krause, H. H., Vaughan, D. A., Miller, P. D., Corrosion and Deposits from Combustion of Solid Waste. Journal of Engineering Power, 95(1):45, 1973.
10. Vaughan, D. A., Krause, H. H., Boyd, W. K., Fireside Corrosion in Municipal Incinerators Versus Refuse Composition. Materials Performance, 14(5):16, 1975.
11. Krause, H. H., Refuse-Derived Fuels. Presented at ASME Joint Power Generation Conference, Sept. 28, 1980.
12. Krause, H. H., Vaughan, D. A., Cover, P. W., Boyd, W. K., Olexsey, R. A., Corrosion and Deposits from Combustion of Solid Waste - Part VI. ASME, Winter Annual Meeting, San Francisco, California, December 10-15, 1978.